NTNU
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# Semi-closed containment systems in Atlantic salmon production

## Comparative analysis of production strategies

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# Preface

This thesis is finalizing the master degree in Marine Technology here at NTNU in Trondheim. I have specialized in Marine Resources and Aquaculture during the last 2 years. Focus these last years has been on the Norwegian aquaculture industry and this thesis is highlighting the possibilities for semi-closed containment production systems floating in sea.

The project thesis autumn 2016, as a pre-project, focused on treatment of intake water to these systems and the experiment Intake 2016, conducted at Nofimas research station at Sunndalsøra. Intentionally this master thesis should have been built directly on the experiment, but some results are still waiting and much was covered in the project thesis, therefore focus shifted a bit during the start up in January and February.

During the process I was included as a co-author on an internal report in CtrlAQUA and I also got the opportunity to present Intake 2016 on CtrlAQUAs annual meeting in Bergen 10th of May. This has been very motivating and I am humble and grateful that I got these opportunities.

I would like to thank everyone at Nofima and CtrlAQUA at Sunndalsøra for including me in their project and for all help along the way. A special thanks to Astrid Buran Holan who took care of everything and gave me responsibility from day one. I would like to thank my supervisor Professor Bjørn Egil Asbjørnslett at Department of Marine Technology for his time, input and tutoring during the entire process. Finally, I would like to thank everyone in my class here at Marine Technology. Without you, this would have been much less worthwhile.

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# Summary

Atlantic salmon farming in Norway are facing huge challenges related to sea lice, mortality and increasing production costs. In the fight against these challenges the Norwegian government are encouraging the industry to develop technological innovations, so it can grow further. Semi-closed containment systems (S-CCS) floating in sea are one of the production systems proposed to face these challenges. Producing Atlantic salmon in S-CCS up to the weight of one kilogram, before transfer to traditional open net pens, has been suggested.

The main difference between a S-CCS compared to a traditional open net pen is the physical barrier that separates the rearing environment from the external environment. This physical barrier also mean that optimal range of rearing parameters like oxygen, $CO_2$, TSS, turbidity, temperature and pH must be ensured by the system. Treatment of intake water and water treatment technology are important to ensure optimal rearing environment.

In this thesis three different production strategies involving production in S-CCS are introduced. Strategy one are based on the suggestion of producing postsmolt up to a weight of one kilogram. Strategy two are including a stage where fish close to market size are moved to S-CCS for the last grow out phase. Strategy three are based on the ongoing development in land based farming. This strategy is including postsmolt production up to a weight of one kilogram in land based systems before the fish are transferred into sea and moved into S-CCS for the last grow out phase. These are the three alternatives in the model.

The Analytic Hierarchy Process (AHP) method are applied to evaluate the alternatives upon the five criteria; Time in sea, Mortality, Cost, Efficiency, Sites and area. The criteria are based on literature and recent research progress. A simple Rank Order Centroid evaluation, applying value functions, were also conducted to compare with the AHP analysis. Sensitivity analysis were performed in the AHP analysis to show the robustness of the results. AHP method favoured strategy one, while the ROC recommended strategy two.

Multiple production strategies and production system will be put into commercial Atlantic salmon production in the years to come. It is likely that these systems will be developed in parallel to exploit the various benefits along the coast. Regulations and constraints will also play an important role in this development.

# Sammendrag

Lakseoppdrett i Norge står overfor store utfordringer knyttet til lakselus, dødelighet og økende produksjonskostnader. I kampen mot disse utfordringene oppfordrer norske myndigheter industrien til å utvikle teknologiske løsninger, slik at næringen kan vokse videre. Semi-lukkede produksjonssystemer (S-CCS) i sjøen er et av alternativene som er foreslått for å håndtere utfordringene. Produksjon av atlantisk laks i semi-lukket produksjonssystemer opp til en kilo før overføring til tradisjonelle åpne merder, har blitt foreslått.

Hovedforskjellen på et semi-lukket system sammenlignet med tradisjonell merd-oppdrett er den fysiske barrieren som skiller oppdrettsmiljøet fra det ytre miljøet. Denne fysiske barrieren betyr også at essensielle produksjonsparametere som oksygen, $CO_2$, TSS, turbiditet, temperatur og pH må opprettholdes av systemet. Behandling av inntaksvann og vannrenseteknologi er viktig for å sikre optimale produksjonsforhold i et semi-lukket anlegg.

I denne avhandlingen presenteres tre forskjellige produksjonsstrategier som involverer produksjon i semi-lukkede system. Strategi en er basert på forslaget om å produsere postsmolt opp til en kilo. Strategi to inkluderer en fase hvor laks nær slaktestørrelse flyttes til et semi-lukket system for siste del av påvekstfasen. Strategi tre er basert på forlenget produksjon på land. Denne strategien inkluderer postsmoltproduksjon, opp til en kilo, i landbaserte systemer før fisken overføres til sjø og flyttes inn i et semi-lukket system for den siste påvekstfasen. Dette er de tre alternativene i modellen.

Metoden Analytisk Hierarki Prosess (AHP) brukes for å evaluere alternativene opp imot de fem kriteriene; Tid i sjø, dødelighet, kostnad, effektivitet, lokaliteter og områder. Kriteriene er basert på litteratur og forskning innenfor fagfeltet. En enkel rangeringsmetode (ROC), ble også anvendt for å sammenligne med AHP-analysen. For AHP-analysen ble det utført sensitivitetsanalyse for å vise resultatets robusthet. AHP-metoden favoriserte strategi en, mens ROC anbefalte å velge strategi to.

Flere produksjonsstrategier og produksjonssystemer vil bli satt i kommersiell drift i årene som kommer. Det er sannsynlig at disse systemene vil bli utviklet parallelt for å utnytte de ulike fordelene langs kysten. Regelverk og forskrifter vil også spille en viktig rolle i denne utviklingen.

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# Abbrevations

| | |
|---|---|
| AGD | Amoebic gill disease |
| AOP | Advanced oxidation process |
| BOD | Biochemical oxygen demand |
| CI | Consistency Index |
| $CO_2$ | Carbon dioxide |
| COD | Chemical oxygen demand |
| CR | Consistency Ratio |
| DO | Dissolved oxygen |
| EM | Eigenvector method |
| FCR | Feed Conversion Ratio |
| $FCR_b$ | Biological Feed Conversion Ratio |
| $FCR_e$ | Economic Feed Conversion Ratio |
| $HO\bullet$ | Hydroxyl radicals |
| HRT | Hydraulic retention time |
| IPN | Infectious Pancreatic Necrosis |
| ISA | Infectious Salmon Anemia Virus |
| NOM | Natural organic matter |
| ORP | Oxidation Reduction Potential |
| RAS | Recirculating Aquaculture System |
| RI | Random Consistency Index |
| S-CCS | Semi-closed Containment System |

| | |
|---|---|
| $TiO_2$ | Titanium dioxide |
| TRO | Total residual oxidants |
| TSS | Total Suspended Solids |
| V-UV | Vacuum Ultraviolet light |

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# Part I

# Introduction and method

# Chapter 1

# Introduction

Aquaculture industry in Norway is facing some enormous challenges. Sealice, escapes and diseases are some of the major issues related to production of Atlantic salmon. While struggling with this problems there is a clear vision from the Norwegian government of growth and increase of aquaculture production in Norway (Olafsen, Winther, Olsen, & Skjermo, 2012). How can the industry fulfill the vision and goal of growth and at the same time take control of the major issues?

Some producers are developing huge structures for exposed aquaculture for the on-growing phase. Others are looking to increase the control of the cultivating environment by developing closed and semi-closed production systems in sea and on land, and to keep the smolt in such systems for a longer period before being transported to open net cages. These developments can change the production chain for salmon and give new opportunities for increased value creation.

So why is it important to develop the aquaculture industry? In 2015 Norway produced approximately 1.4 million ton seafood from aquaculture, with an estimated value of 47 billion NOK (Statistisk Sentralbyrå, 2016). Aquaculture industry is one of the fastest growing industries in Norway and it is estimated that the growth will be formidable towards 2050 (Olafsen et al., 2012). At the same time there has been a volume stagnation, as seen in figure 1.1. The last 3-4 years production volume of Atlantic salmon in Norway has been steady around 1.2 [million ton] (Statistisk Sentralbyrå, 2016). For Norwegian export and trade it is absolutely critical to be leading the development of aquaculture, especially when it comes to Atlantic Salmon. Norway must continue to deliver top quality products and at the same time optimize the growth of Atlantic salmon sustainable. This requires growth and increase in production.

In the hunt for optimal sustainable production it is multiple solutions put into testing and this study will focus on the semi-closed containment systems (S-CCS) being introduced and their possible effect on the production cycle of Atlantic salmon. Besides S-CCS this thesis will include some information about production of postsmolt on land in recirculating aquaculture systems.

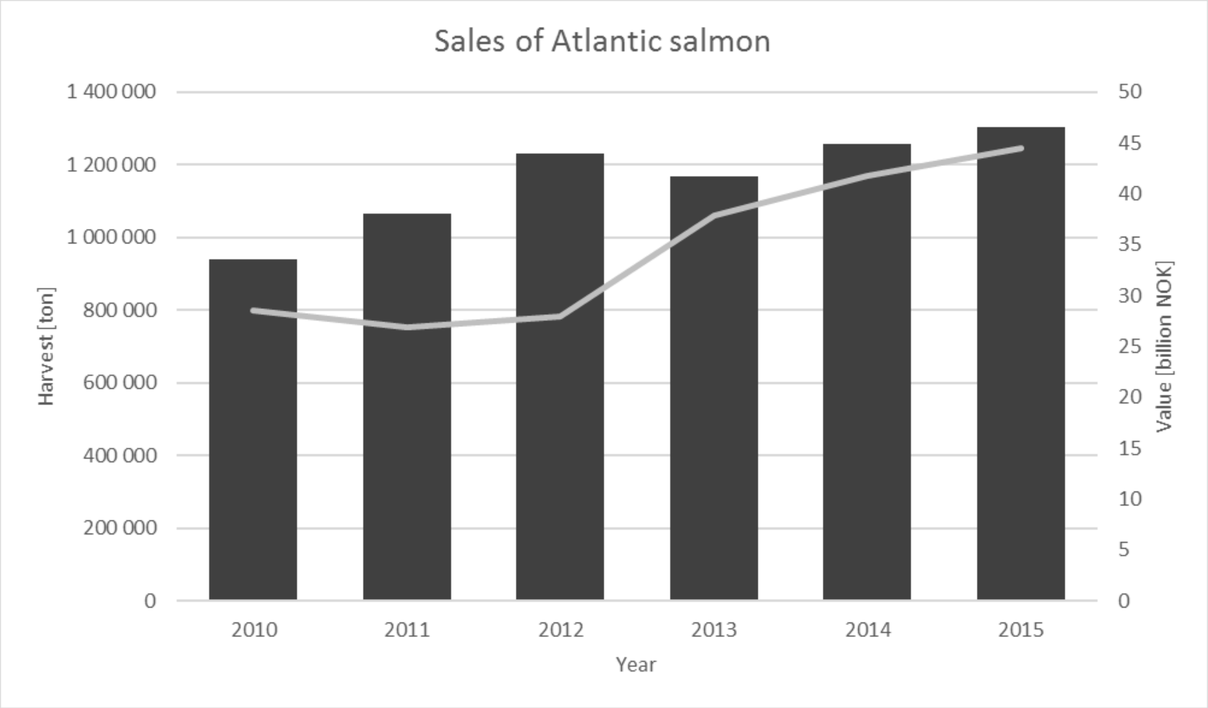


Figure 1.1: Amount and value of harvested Atlantic Salmon from 2012 until 2015 (Statistisk Sentralbyrå, 2016). Harvest volume are represented by diagram chart, while value are represented as the line chart.

## 1.1 Background

Autumn 2016 CtrlAQUA's project Intake 2016 took place, resulting in a project thesis focusing on treatment of seawater to semi-closed aquaculture systems, including a pilot scale experiment at Nofima Sunndalsøra (Haaland, 2016). The focus on treatment of intake water is more important than ever (Joensen, 2017). For closed systems to perform optimal it is absolutely essential that there are no harmfull bacteria entering the rearing environment.

In Intake 2016 several treatment configurations where tested with focus on delivering a safe water supply to the rearing environment, as required in the regulations (Fiskeridepartementet, 1997). The experiment included monitoring of by-products, turbidity, UV-transmittance, colony forming units and determining type of bacteria throughout the system components. Relevant results from the experiment are presented as a summary later. This thesis will focus more on the possibility to introduce S-CCS in todays production regime, but will include parts about water treatment.

Semi-closed containment systems are primarily being developed to be able to produce bigger smolts than applied today, and to reduce the total time salmon are exposed in open net pens (Mathisen, 2016). Reducing the time in open net pens reduces the exposure for sealice and possible diseases. This could also affect the effectiveness of the open net pen production sites and improve the salmon production cycle.

Figure 1.2: Neptun, a prototype semi-closed system from Marine Harvest and Aquafarm Equipments. The size and design of this system is used further on in this study. This type of system are so far being operated much closer to shore than is the case for traditional open net pen systems. (Retrived 16.02.2017, from: http://kyst.no/nyheter/satt-ut-smolt-i-lukka-merd/)

Larger smolt has shown to be more robust and to handle the transfer to open net cages in seawater better, resulting in a higher degree of survival compared to todays average smolt size (Ytrestøyl et al., 2014). Handeland, Calabrese, Breck, and Terjesen (2015) presented survival in postsmolt production to be 99% up to 2 kg when produced in certain prototypes of semi-closed production systems. Increasing problems related to diseases and sea lice is also a huge contributor to the growing production cost for the salmon industry in Norway. Iversen et al. (2015) estimated the cost of sea lice to be around 5 billion NOK in 2015, while Rødseth (2016) and Stingray Marine Solutions estimated it to be up to 8 billion NOK. Rapidly increasing production cost is one of the main drivers for innovation and development of new concepts and systems.

After several prototypes being tested, like Marine Harvests Neptun at Molnes, Nekton Havbruks flexibag and Lerøys Preline, it is clear that this type of production is possible and that there will be future projects within this topic (Joensen, 2017). It seems it is not without problems as there has been detected diseases (Breck, 2014). S-CCS are dependant on a safe supply of intake water, meaning there has to be some kind of water treatment before the flow enters the rearing environment. According to A. Nilsen, Nielsen, Biering, and Bergheim (2016) sealice seems to be less of a contributor to the discussion regarding the need to treat intake water, but Handeland et al. (2015) found that these parasites still finds their way into the rearing tanks.

## 1.2 Problem description

As the salmon industry evolve it seems focus on controlling the production environment and reducing the negative external effects increases. Hence focus on treatment of intake water is increasing. New production systems, like S-CCS in sea and landbased farming, get a lot more attention than earlier.

This master thesis is based on the project thesis, and the related experiment focusing on treatment of seawater. A part of this report will focus on the important parameters for semi-closed and closed production system to be able to produce. Another part of the master thesis will be to look into how S-CCS and landbased farming can supplement and interact with todays production regime of Atlantic salmon. How can it fit in, and what can be the benefits of implementing these systems?

The main focus will be to see how the introduction of S-CCS can influence the salmon production chain with respect to reducing the time salmon is exposed in sea, mortality, investment cost, more effective use of open net production sites and sites and area used in production. Is it only in the period from 100 gram to one kilogram it could be beneficial to operate with S-CCS or can it be other parts of the production chain that can benefit from S-CCS? Could this increase the effectiveness of sites and possibly increase production in volume? This are questions this master thesis will try to highlight, discuss and answer. Different strategies for applying S-CCS and landbased farming in todays production regime will be proposed and evaluated based on key criteria.

## 1.3 Objective

The overall goal is to highlight the possibilities and challenges related to S-CCS. Possibilities being the opportunity of increased and more efficient production of Atlantic salmon. Focus related to the challenges will be on safe water supply to the rearing environment, water quality and water treatment, increasing production cost and how to fit S-CCS into todays production regime. In order to fulfill this, the following objectives are to be met:

**1.** Introduce semi-closed containment system and Atlantic salmon production. How can S-CCS fit into todays production regime. The literature review will form the basis for strategies and criteria to be evaluated.

**2.** Propose the different production strategies using S-CCS and landbased production. Do a comparative analysis of these strategies using two different methods, Rank Order Centroid and Analytic Hierarchy Process.

**3.** Present results from the comparative analysis and discuss if these proposed strategies are likely to be introduced in production of Atlantic salmon.

## 1.4 Scope and limitations

Rules and regulations related to S-CCS in sea are limited or none existing. Hence there will be assumptions related to density, fallowing, production volume and other operational parameters related to the evaluation of criteria.

For the comparative analysis of the different production strategies the focus will be on reduced production time in open sea, mortality, investment cost, efficiency and area and site demand.

The main limitation in this master thesis is the fact there are no S-CCS in commercial production today, as they are all prototypes. This limit the access to data, so estimates and assumptions are taken from research and published papers/literature, as well as assumptions from the author.

Focus will be on describing and introducing semi-closed containment systems to Atlantic salmon production. Focus will not be in depth on the methods applied, but to show how these methods can be utilized in a potential strategy problem regarding S-CCS.

## 1.5 Claims

Based on the background, problem description and objective there has been proposed some claims related to semi-closed containment systems and their potential. This study will highlight related literature, testing and preliminary results, which will form the basis for answering these claims.

**1.** Introducing S-CCS to Atlantic salmon farming can increase production volume and increase efficiency of sea sites.

**2.** S-CCS can reduce the amplitude in the cyclic production of salmon and keep a more stable production near maximum allowed biomass.

**3.** S-CCS will reduce exposure in open sea and handling of fish required, resulting in a higher degree of fish welfare and health.

# Chapter 2

# Method

The various parts in this master thesis are conducted in slightly different ways and in this chapter the methods applied in the study are presented.

Presenting S-CCS is a literature review presenting the recent research on S-CCS and the challenges and opportunities related to this type of system. These findings forms the basis for the criteria and alternatives proposed. The comparison of production strategies are also based on literature, conferences and personal communication with partners in the industry. Rank Order Centroid and Analytic Hierarchy Process are the methods applied in this study to evaluate the strategies. Sections regarding the treatment of intake water are based on the experimental results and literature review conducted in the project thesis (Haaland, 2016).

## 2.1 Intake 2016

The quality of the water can influence the efficiency of the treatment technologies, and can lead to formation of disinfection byproducts, e.g. by applying ozone in seawater containing bromide. The main focus of Intake 2016 was to evaluate the influence of seawater quality on the efficiency of intake water treatment for closed-containment aquaculture systems. Different treatment technologies suited for intake water treatment were evaluated, e.g. ozonation, filtration, UV irradiation and AOP treatment. The efficiency was described by evaluating the effect on bacterial number and microbial characterization, particles and organic material. Furthermore, the formation of residual oxidants and by-products after ozonation and AOP treatment was assessed.

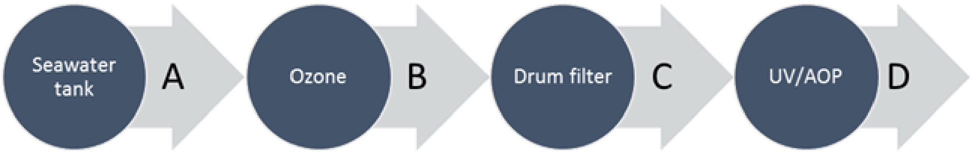


Figure 2.1: Schematic view of system tested in Intake 2016

(a) Drumfilter (b) UV (c) AOP

Figure 2.2: Pictures from the pilot scale experiment at Nofima, in Sunndalsøra

### 2.1.1 Experimental setup testing treatment methods

The experiment was performed at the Nofima Research Station for Sustainable Aquaculture, Sunndalsøra, Norway. Untreated seawater from 40 m depth in Tingvollfjorden was pumped into a holding tank. This tank was also used to add wastewater from the research station, consisting of fish fecal matter, feed spill and microbial flocs, increasing the particle concentration for some of the tests. Multiple tests where conducted using the different components of the system, with both low and high total suspended solids (TSS) concentration.

Intake 2016 form the basis for more projects, research and testing regarding treatment of inlet water to closed and semi-closed containment systems. Treatment of intake water might be essential to make the S-CCS work as it is intended to.

## 2.2 Comparative analysis

Strategies proposed and to be evaluated are; postsmolt in S-CCS, postsmolt and close to market size fish in S-CCS, and landbased postsmolt with close to market size fish in S-CCS floating in sea. Details about the strategies and criteria will be described. The methods used to evaluate the different strategies will now be presented.

Table 2.1: Strategies being evaluated

| **Strategy** | **Number** |
|---|---|
| Postsmolt in S-CCS | I |
| Postsmolt and close to market size fish in S-CCS | II |
| Postsmolt landbased and close to market size fish in S-CCS | III |

Table 2.2: Criteria and level of importance

| Criteria | Level of importance |
|---|---|
| Time in sea | 1 |
| Mortality | 2 |
| Cost | 3 |
| Efficiency | 4 |
| Area and sites | 5 |

The comparative analyse of the three different strategies, in table 2.1, are to be evaluated upon the five criteria seen in table 2.2; time in sea, mortality, cost, efficiency and sites and area.

The methods applied to evaluate the strategies are Rank Order Centroid (ROC) and Analytic Hierarchy Process (AHP). ROC can be described as a Simple Multi Attribute Rating Technique Exploiting Ranks (SMARTER) (Edwards & Barron, 1994), while AHP often is referred to as a Multiple-criteria decision-making (MCDM) method (Saaty & Vargas, 2012).

### 2.2.1 Rank Order Centroid

The first method applied to evaluate the strategies is the ROC. This is a fairly simple and easy method to give attributes a numerical weight and score. For the decision-maker it is often easier to give criteria a ranking, but it can be harder to give each criteria a weight. Rank order centroid convert ranking to weights. Ahn (2011) describes the ROC weights in his paper:

> *The ROC weights are called the centroid (i.e., center of mass) weights in efforts to seek to identify a single set of weights that is representative of all the possible weights combinations that are admissible and consistent with the established linear inequality constraints on the weights.*

F. H. Barron and Barrett (1996) suggested the weighting method with this mathematical formula:

$$w_i = \frac{1}{n}\sum_{j=i}^{n}\frac{1}{j} \qquad i = 1, 2, ..., n. \tag{2.1}$$

In this study there are 5 criteria, $n = 5$. The criteria ranked as most important will be weighted as follows:

$$w_1 = \frac{1}{5} * (\frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \frac{1}{5}) = 0.457 \tag{2.2}$$

For the second most important criteria the weighting will be:

$$w_2 = \frac{1}{5} * (\frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \frac{1}{5}) = 0.257 \tag{2.3}$$

Continuing on with this, gives the following table:

Table 2.3: Criteria with ranking and weight

| **Criteria** | **Ranking** | **Weight** |
|---|---|---|
| Criteria #1 | 1 | 0.457 |
| Criteria #2 | 2 | 0.257 |
| Criteria #3 | 3 | 0.157 |
| Criteria #4 | 4 | 0.090 |
| Criteria #5 | 5 | 0.040 |
| Total | | 1.000 |

The next step in the ROC process is to establish individual value functions for each criteria. This can be done by determining a scale, form and to normalize the function (Edwards & Barron, 1994). For instance can criteria #3 have a minimum at 5 [-] and a upper limit at 50 [-]. By saying the function is linear we assume that the criteria is linearly related to the values. It is then possible to normalize the function saying $C_3(50) = 0$ and $C_3(5) = 1$. It is then easier to give score to each alternative at the criteria #3 as figure 2.3 displays.

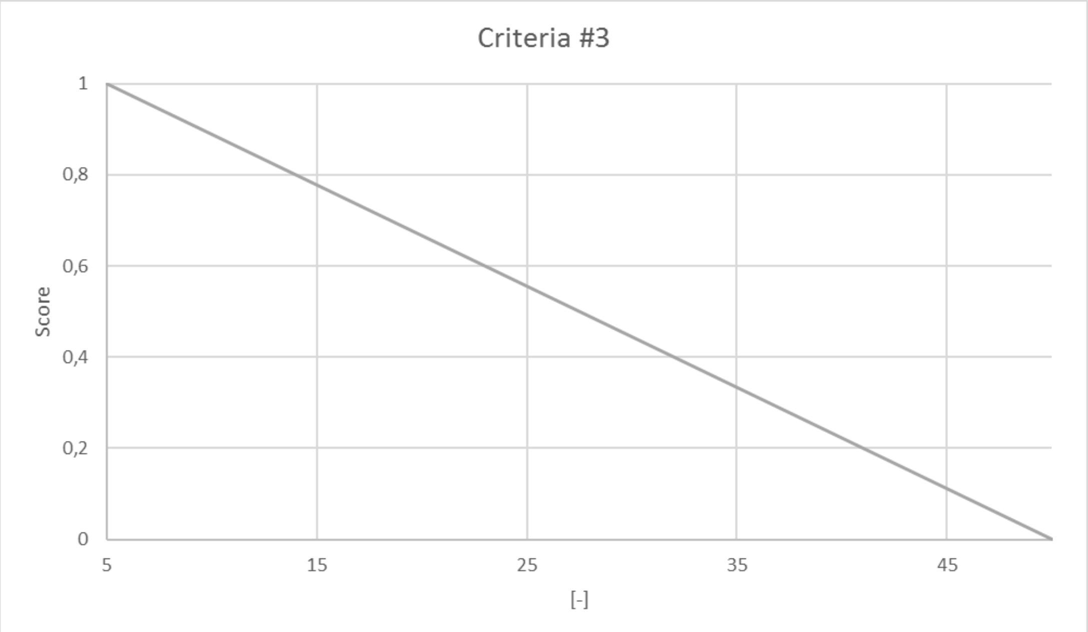


Figure 2.3: An example of a value function. Linear and normalized.

After weights and value functions are developed the decision maker judge the alternatives individual score on each criteria and calculate the total score. Equation 2.4 shows how total score is calculated for each alternative:

$$\text{Total score} = (w_1 * s_1) + (w_2 * s_2) + (w_3 * s_3) + .... + (w_n * s_n) \tag{2.4}$$

w = weight
s = score, normalized
n = number of criteria

### 2.2.2 Comments to ROC method

As shown the ROC is easy to follow, but it gives dispersed weights which can lead to the lowest rankings almost being eliminated to effect the analysis if there are many criteria in the problem (F. H. Barron & Barrett, 1996). Determining the type of value functions are also important, since an exponentially function versus a linear function effects the score. Scores are also highly dependant on the decision makers viewpoint and which scores thought to be decisive. This must be taken into consideration when using this method. ROC is a quick method to get an indication of a solution for the decision maker.

### 2.2.3 Analytic Hierarchy Process

Saaty (1977) presented a scaling method for priorities in hierarchical structures in his paper, forming the basis for the AHP. It is best described as a multi-criteria decision method and has been applied in various fields like information and communication technology (Dede, Kamalakis, & Varoutas, 2011), engineering (Kengpol & O'brien, 2001), corporate strategy (Saaty & Vargas, 2012), industry (Noci & Toletti, 2000) and resource allocation (Saaty, 1980).

AHP is a technique coping with complex decisions problems, by applying a framework for decomposing the problem into a hierarchy of criteria and alternatives. The goal of AHP is to quantify a decision makers preferences by their judgments on qualitative and quantitative criteria. A solution is achieved through relative priorities of criteria and alternatives, and a mathematical combination of these judgments.

AHP is simple, yet more complex than rank order centroid and is based on the pairwise comparison between the criteria. Each criteria is compared with all the other in the group and given a score representing the level of importance relative to the comparing criteria (Saaty, 1980). The level of importance score is, as seen in table 2.4, categorized between 1 and 9.

Table 2.4: The Saaty rating scale. Level of importance and their scale (Saaty, 1980).

| Scale | Level of importance |
|---|---|
| 1 | Equal |
| 3 | Moderate |
| 5 | Strong/essential |
| 7 | Very strong |
| 9 | Extreme |
| 2,4,6,8 | Inverse comparison |

Figure 2.4 shows how a hierarchy structure might look like and how the alternatives are related to all the criteria. It is also possible to insert sub-criteria, making the analyse more complex.

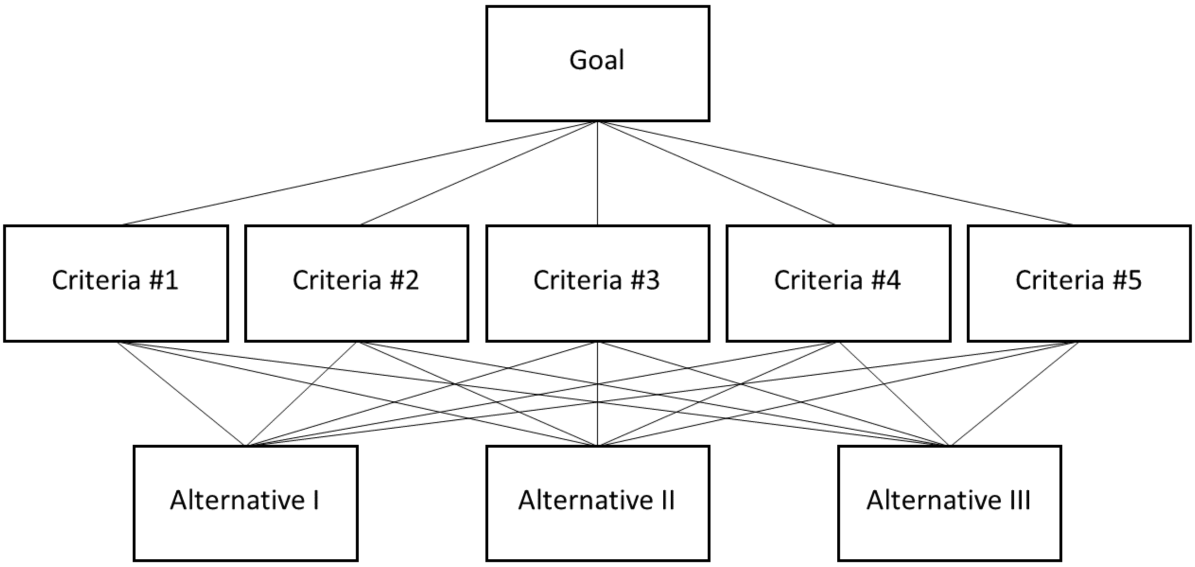


Figure 2.4: Structure of the hierarchy in AHP.

First the problem to be analysed must be established and formulated so it is possible to divide it into a hierarchy with criteria and alternatives. In this study the objective is established by the author in the introduction as a response to the development within this discipline and the strategies and possibilities that exist. This is the first level in the hierarchy structure. The second level includes the number of criteria and specifications of criteria are determined. This are based on the literature review in this study. An additional level can be added, with sub-criteria, to specify features even more. In this study the criteria in level two are covering enough to give a description of the objective. When the hierarchical structure is constructed the pairwise comparisons are conducted at each level. The pairwise judgments are performed by the author in this case.

Table 2.5: Comparison matrix set up for criteria.

| | **Criteria #1** | **Criteria #2** | **Criteria #3** | **Criteria #4** | **Criteria #5** |
|---|---|---|---|---|---|
| **Criteria #1** | $a_{11}$ | $a_{12}$ | $a_{13}$ | $a_{14}$ | $a_{15}$ |
| **Criteria #2** | $a_{21}$ | $a_{22}$ | $a_{23}$ | $a_{24}$ | $a_{25}$ |
| **Criteria #3** | $a_{31}$ | $a_{32}$ | $a_{33}$ | $a_{34}$ | $a_{35}$ |
| **Criteria #4** | $a_{41}$ | $a_{42}$ | $a_{43}$ | $a_{44}$ | $a_{45}$ |
| **Criteria #5** | $a_{51}$ | $a_{52}$ | $a_{53}$ | $a_{54}$ | $a_{55}$ |

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & ... & a_{1n} \\ a_{21} & a_{22} & ... & a_{2n} \\ ... & ... & ... & ... \\ a_{m1} & a_{m2} & ... & a_{mn} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & ... & a_{1n} \\ 1/a_{12} & a_{22} & ... & a_{2n} \\ ... & ... & ... & ... \\ 1/a_{1n} & 1/a_{2n} & ... & a_{mn} \end{bmatrix} \tag{2.5}$$

The basic of the AHP is to construct a matrix expressing these relative values of attributes and then normalize the matrix. In this case there are five criteria and three alternatives to be evaluated upon the criteria. The first stage is to create the matrix where criteria is compared against each other. In table 2.5 the comparison matrix is presented. Element $a_{mn}$ represents the importance of the $m^{th}$ criterion relative to the $n^{th}$ in the matrix. If $a_{mn} >$, then m criterion is more important than n. The matrix in equation 2.5 displays this relationship.

The eigenvector method (EM) is applied to weight and adjust assignments from the comparison matrix. A comparison matrix is defining the level of importance for one criterion compared to the others. The eigenvector solution is applied to determine the vector of priority and to calculate the consistency of the comparisons conducted by the decision maker (Saaty & Vargas, 2012). Sen (1998) stated that the eigenvector had to satisfy equation 2.6.

$$W_2 = bW_1 \tag{2.6}$$

$W_1$ is the weight in top value of the hierarchy structure, while $W_2$ is the weight vector in level two. b is the eigenvector for elements in level two and is equivalent to the normalized eigenvector from the comparison matrix. Normalizing the comparison matrix is necessary, and the entries are calculated (Saaty, 1980):

$$\overline{a}_{mn} = \frac{\overline{a}_{mn}}{\sum_{m=1}^{n} a_{mn}} \tag{2.7}$$

Average of the rows, in the normalized comparison matrix, is then applied to get the priority vector as seen in equation 2.8.

$$\mathbf{W}_m = \frac{\sum_{m=1}^{n} \overline{a}_{nm}}{n} = \begin{bmatrix} W_1 \\ W_2 \\ \cdots \\ \cdots \\ \cdots \\ W_m \end{bmatrix} \tag{2.8}$$

To ensure that the comparison and relative values are consistent and not totally random put together it is necessary to calculate the Consistency Ratio (CR). The consistency ratio is the consistency index divided by the corresponding matrix random index developed by Saaty (1980). For a consistent reciprocal matrix $\lambda_{max} = n$. This means the largest eigenvalue is equal to the size of the matrix. The Consistency Index (CI) is then the deviation in this equation (Saaty, 1980):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2.9}$$

The Random Consistency Index (RI) developed by Saaty (1980) can be find in tables. A section of this is shown here:

Table 2.6: A section of the Random Consistency Index by Saaty (1980).

| **n** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| **RI** | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.51 |

Now that the CI is calculated and the appropriate RI are found, we can calculate the CR and define if the pairwise comparisons are consistent and not totally random. This is done by diving the CI on RI.

$$CR = \frac{CI}{RI} \tag{2.10}$$

Saaty (1980) suggest that the comparisons are consistent if the CR $\leq 0.10$. Sometimes a result higher, but close, to 0.1 must be accepted. In most cases the comparison should be reviewed once more if higher, especially if the result is far above 0.1. A CR of zero means the matrix is perfectly consistent. After doing these calculations for the comparison matrix the alternatives must be evaluated in the same manor for each criteria, in this case five.

The basic of the AHP method and the steps shown are as follows (Saaty, 1980; Sen, 1998):

- Build hierarchy structure of the problem
- Develop the comparison matrix
- Calculate the normalized eigenvector and relative priority vector
- Check consistency
- Give alternatives their respective score
- Based on the criteria preference matrix and level of importance vector the alternatives are ranked

### 2.2.4 Comments to the AHP method

Strengths of the AHP-method is that it is scalable and the hierarchy structure can be adjusted easily to fit many different decision making problems. The method is not data intensive, meaning there are no need for complex software programs to conduct the analysis, even though it will make computations easier (Saaty & Vargas, 2012).

AHP may have problems with interdependence between the criteria and alternatives resulting in an inconsistency between ranking and judgment, and redundant comparisons of alternatives (Bana E Costa & Vansnick, 2008). The method has also been criticized for the possibility of rank reversal when alternatives are deleted or new alternatives are introduced (Sen, 1998). The method assume that the alternatives are independent which implies preservation of ranks. It then follows that criteria are not dependant on the alternatives (Saaty & Vargas, 2012).

The AHP method is applied in many fields of study as corporate policy and strategy, resource management and political strategy. It has also been used in the agricultural sector (Pirazzoli and Castellini, 2000; Gómez-Limón Rodríguez, Arriaza Balmón, and Gallego-Ayala, 2011). Based on these comments, the method is applicable for decision making on a strategy level in aquaculture. Despite the issues related to the method, AHP can produce acceptable answers when applied with care (Saaty and Vargas, 2012; Vaidya and Kumar, 2006).

## 2.3 Statistics and strategy comparison

Microsoft Excel has been used to sample raw data from Directorate of fisheries and SSB, as well as to do calculations regarding the different strategies and conduct the evaluation of alternatives using ROC and AHP. Sensitivity analysis were conducted using the free software SuperDecisions v.2.8 from The Creative Decisions Foundation.

# Part II

# Literature review

# Chapter 3

# Semi-closed containment system

Semi-closed containment system floating in sea arise as an alternative or possibly a supplement to the traditional production of Atlantic salmon in open net pens. New production strategies and systems are under development because of the demanding production conditions seen in traditional production. Prolonged production of smolts, both in S-CCS in sea and on land in recirculating aquaculture systems (RAS), are being proposed (Iversen, Andreassen, Hermansen, Larsen, and Terjesen, 2013; Kolarevic et al., 2014; Terjesen et al., 2013).

## 3.1 Description

What differentiates S-CCS from a traditional open net pen system is the physical barrier that separates the rearing environment from the external environment. This physical barrier can be made of different materials, like concrete, glass-reinforced plastic and soft polymer fabric (Aquafarm Equipment, n.d.; Martinsen, 2015).

In semi-closed system you still rely on nature providing the right temperature, bringing enough oxygen into the tank and removing waste. Water entering a semi-closed system only get used once before it will bring with it waste and leave the rearing environment. Compared to an open net pen system it might have a higher production rate because of the increased control. Some of the advantages of semi-closed systems is a more efficient feed rate, water replacement, temperature control and detection of diseases. On the other hand there are larger construction costs and high demand for monitoring (Lekang, 2013).

Table 3.1: Categories of S-CCS in sea (Rosten et al., 2011). Category I are the simplest of systems, while category IV are more technological demanding. Demands for lower categories are also included in higher categories.

| **Category I** | **Category II** | **Category III** | **Category IV** |
|---|---|---|---|
| Physical barrier | Double escapes security | Removal of fish pathogens from intake water (UV) | RAS |
| Controlled intake of water | Removal of lice larvae from drains with filter | | Reduce water consumption |
| Controlled drainage of water | Purification of sludge | | |

Rosten et al. (2011) proposed a categorization of S-CCS, as seen in table 3.1. The demands for lower categories are also applied to categories higher up. The higher the category, the more control of rearing environment are required. Systems that are being tested today can be put into category II and III. Implementation of RAS in production systems floating in sea has yet not been tested, but can be of interest in the future.

Semi-closed containment systems (S-CCS) are today dependant on huge water flows through the inlet to achieve the wanted production environment. For instance Marine Harvests system, Neptun at Molnes in Skånevik, require enormous water flow. It is dependent on up to 400 $m^3$/min for the 21 000 $m^3$ production unit (Calabrese et al., 2016). Operating as an flow-through system, with no recirculation, this can be challenging with respect to the possibilities of treating the intake water before entering the rearing environment as well as energy required. The huge demand for water flow is mainly related to the fact that inlet water, taken at 10-30 meters depth, is the primary source of dissolved oxygen.

The prototype systems being tested the last couple of years and to the present are currently not using any treatment of inlet water, except coarse mechanical filters (Handeland et al., 2015; Rosten et al., 2011). Since treatment might give strict restrictions to flow and capacity, there might be an option to implement recirculating systems (RAS), reducing the amount of intake water needed, resulting in a category IV system in table 3.1.

Potential invasion of pathogenic bacteria is also a challenge for S-CCS in sea. Especially bacteria such as *Moritella viscosa* and *tenacibaculum* potentially causing winter ulcers can be problematic (Hjeltnes, Walde, Jensen, & Haukaas, 2016). This will be covered further and in more detail in section 4.

## 3.2 Design

Today there are companies developing S-CCS with different capacity and design. Many are still only on the drawing board, but some are already being tested for the second and third time. Terjesen (2017) found that 9 different S-CCS are actually built and put to testing while there are over 14 different more designs planned.

As seen in table 3.2 there are different approaches to the development of S-CCS floating in sea when it comes to choice of material. Both flexible fabric and hard structures in glass-reinforced plastic are developed. Arguments for flexible fabric design are that they are cheap and easy to implement on existing sites.

Most of the new S-CCS prototypes are designed to produce Atlantic salmon up to one kilogram, and they are thought to be put into the postsmolt phase in the production chain. Other systems, like Marine Harvests proposed S-CCS Donut, yet to be produced and tested, can intentionally be put to use in the last part of the production phase, approximately from 3.5 [kg] to 5 [kg] (Joensen, 2017). One reason for testing this strategy might be the high operational cost related to handling, like delousing, of fish close to market size 4-5 [kg], as well as the increased weight of dead-fish (J. Pettersen, 2017).

Every system mentioned in table 3.3 have coarse inlet filtration on the intake water, as required by regulations (Fiskeridepartementet, 1997). No one have other specified water treatment of intake water, like ozone, drum filter or UV. Joensen (2017) stated that testing of the Neptun prototype revealed the need for treatment of the intake water to ensure a safe water supply to the production unit. The next model of Neptun will most likely be equipped with drum filter and UV treatment on each of the four inlet pipes (Joensen, 2017), as proposed by CtrlAQUA in their INTAKE 2015 report.

Table 3.2: Table of the 9 S-CCS built and the material applied

| **Name** | **Material** |
|---|---|
| Agrimarine | Glass-reinforced plastic |
| Akvadesign | Flexible fabric |
| AquaDome | Glass-reinforced plastic |
| Ecomerden | Flexible fabric |
| FishGlobe | Polyethylen |
| HDN | Flexible fabric |
| Neptun | Glass-reinforced plastic |
| Preline | Glass-reinforced plastic |
| SalmonHome no.1 | Concrete |

Table 3.3: Specifications for some of the actual S-CCS prototypes being tested (Martinsen, 2015; Handeland, 2016; Terjesen, 2017).

| **System** | **Volume** [m$^3$] | **Capacity** [kg/cycle] | **Density** [kg/m$^3$] | **Add O$_2$** [-] | **Size** [kg] | **Amount** [fish] | **Flow** [m$^3$/min] |
|---|---|---|---|---|---|---|---|
| **Neptun*** | 21000 | 1575000 | 75 | Yes | 1 | 1575000 | 400 |
| **Preline** | 2000 | 150000 | 75 | Yes | 1 | 150000 | 660 |
| **Akvadesign** | 6000 | 300000 | 50 | Unknown | 1 | 300000 | Unknown |
| **HDN*** | 3000 | 225000 | 75 | Yes | 1 | 225000 | Unknown |
| **Ecomerden** | 5000 | 400000 | 80 | Yes | 1 | 400000 | Unknown |
| **Agrimarine** | 5500 | 412500 | 75 | Yes | 1 | 412500 | Unknown |
| **Aquadome** | 5560 | 417000 | 75 | Unknown | 1 | 417000 | Unknown |
| **Salmon Home no 1** | 1000 | 60000 | 60 | Yes | 1 | 60000 | Unknown |
| **FishGlobe** | 3500 | 250000 | 71 | Yes | 1 | 250000 | Unknown |

*To estimate potential capacity, density is set to 75 [kg/m$^3$]. Maximum recommended by Calabrese et al., 2017, and assumed to be legal in this thesis.

Not all information about the prototypes are available, so in table 3.3 there are made some assumptions based on research results related to maximum density without compromising fish health and welfare (Calabrese et al., 2017). These recommendations are specific for given fish weight ranges, but in this study they are assumed to be valid up to five kilogram. This is done to approximate capacity and production volume for the given systems.

To illustrate the many different designs being introduced as optimal solutions, some of them are presented in the figures below (3.1, 3.2a, 3.2c, 3.2b, and 3.2d).

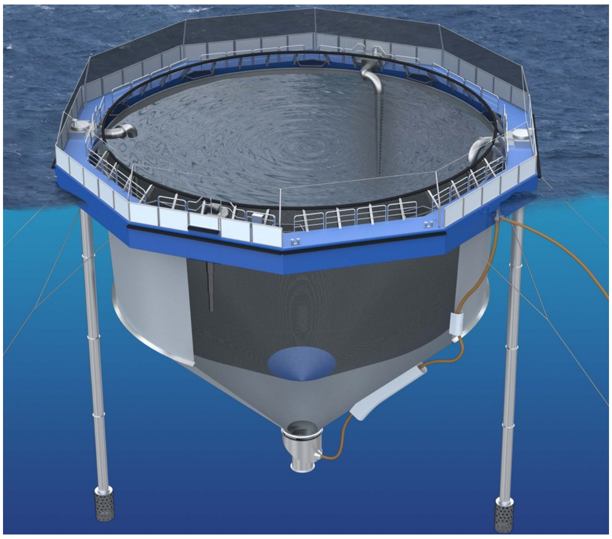
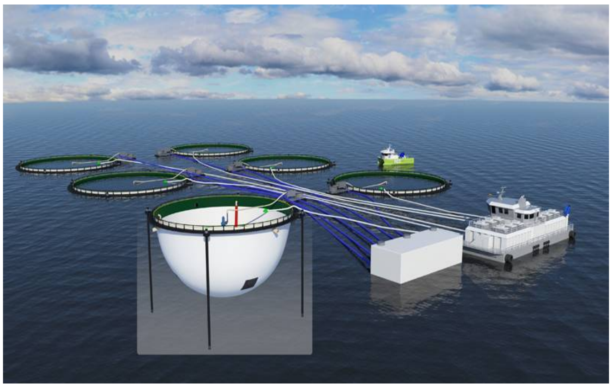
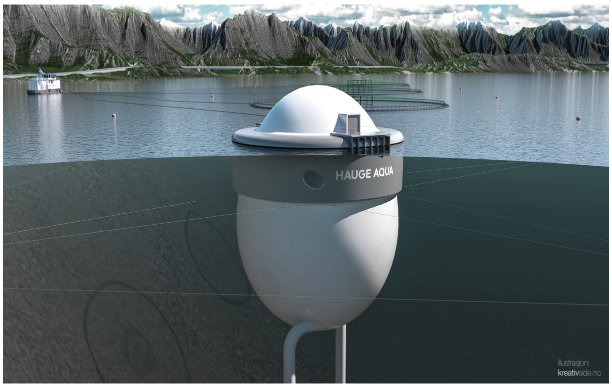


Figure 3.1: S-CCS from Ecomerden AS. (Retrieved 28.02.2017 at http://www.ecomerden.no)

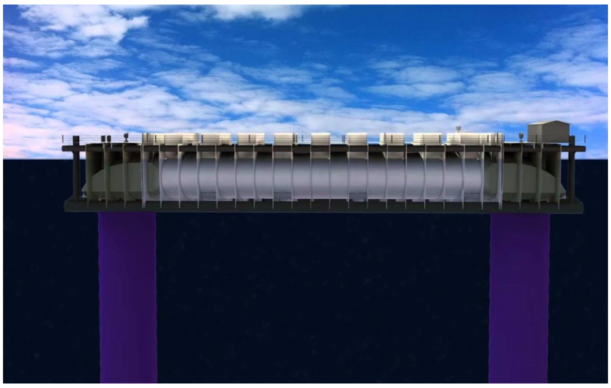


(a) Design from Botngaard.

(b) Salmon Home No 1 from Fishfarming Innovation.



(c) The Egg from Hauge AS and Marine Harvest.



(d) S-CCS from Preline Fishfarming System.

*Retrieved 28.02.2017 at http://www.botngaardsystem.no, http://www.fishfarminginnovation.com, http://www.haugeaqua.com and http://www.preline.no

## 3.3 Important parameters for production in S-CCS

Before going into details about water treatment to S-CCS, advantages of different technologies, we must have a common understanding of the important water quality parameters for aquaculture production. In this case farming of Atlantic Salmon in S-CCS. The review of these parameters does not cover all applications, but is especially oriented towards farming. It is important to understand that different species, temperature regimes and production systems makes any listing of water quality parameters only recommendations (Timmons, Ebeling, Wheaton, Summerfelt, and Vinci, 2010).

The focus on water quality is increasing as the aquaculture industry evolves into more intensive production. When trying to optimise the production, an increase in production density will require exquisite water quality, and quality of the water flowing through the rearing unit will degrade throughout the system. Optimised production means to maximise the growth rate of the fish. In open net cages it is difficult to improve or control the water quality, but in semi-closed and closed system the improvement of water quality are possible and extremely important for production. Another important factor when it comes to controlling the rearing environment is the increased focus on environmental impacts from aquaculture industry (Paisley et al., 2010).

Controlling the water quality gives an opportunity to control the effluent from the facilities and reduce the impact on the environment (Lekang, 2007). It is also interesting to see if it is possible to use the effluent waste material in production of bio-fuel, fertilizer etc. This part will not be further discussed in this report, but will most certainly be of interest in the future.

The difference between open net cages and semi-closed containment systems are mainly the need to use energy to deliver the recommended levels of important parameters in the closed system. While the open net cages are self-provided with oxygen, waste removal, flow and CO2 removal the closed systems are highly dependant on technical solutions to provide the recommended levels of these parameters. Svåsand et al. (2016) presented table 3.4, identifying risk, sources of risk and the consequences related to closed systems.

As seen in table 3.4 there are some parameters with high degree of importance, like oxygen, particles, CO2 and ammonia. If these parameters reach levels outside the tolerance limit for the given specie it could be crucial for production, resulting in high mortality. Semi-closed and closed systems are highly dependant on stable production environment, with focus on levels of these parameters (Rosten et al., 2011).

Table 3.4: Risk, sources of risk and consequences related to closed systems (Svåsand et al., 2016).

| **Risk** | **Source of risk** | **Consequence** |
|---|---|---|
| High particle density | Feces and feed particles | Gill injuries |
| Increased internal infection | Low water exchange | Disease and higher mortality |
| Oxygen deficiency | Low water flow or low oxygen supply | Decreased stress tolerance, loss of control, suffocation |
| CO2 | Operating errors | Suffocation |
| Ammonia | Operating errors | Poisoning |
| Stress | High fish density | Increased oxygen consumption and decreased tolerance to further stress and pathogens |
| Lack of space | High fish density | Wear on fins, bleeding and subsequent infections, imparied swimming ability |

### 3.3.1 Oxygen

Of all the parameters listed oxygen is definitely the most crucial one. Without enough oxygen in the water the fish will get negative physiological effects. The fish needs oxygen for basic metabolism and food conversion. To specify we are talking about dissolved oxygen (DO), meaning the available oxygen for the fish. At higher temperatures the fish needs higher oxygen concentration than when temperatures are low. This is opposite of what nature gives, because at low temperatures the oxygen concentration are high and at high temperatures the oxygen concentration are low (Timmons et al., 2010). Because of this it is even more important to monitor oxygen levels and temperature. Figure 3.3 display the relationship between oxygen consumption, body weight and water temperature.

$$\text{TSF [kg/day]} * \text{ODF [kg oxygen/kg feed]} = \text{TOD [kg/day]} \tag{3.1}$$

TSF = Total system feed
ODF = Oxygen demand factor
TOD = Total oxygen demand

Oxygen is slightly soluble in water, which means the fish needs to use a lot of energy to remove the dissolved oxygen from the water. The solubility will decrease as temperature and salinity increase. Oxygen demand can be calculated when you know the system flow and system daily feed. Timmons et al., 2010, apply a Oxygen Demand Factor (ODF) of 0.6 [kg oxygen/kg feed] when doing the computations.

When we know the total oxygen demand in the system in [kg/day] it is straight forward to convert it to [mg/min] or [mg/L], given that you have the system flow. One important aspect in equation (3.1) is that the amount of feed are the deciding design factor. In real systems the dissolved oxygen will be monitored continuously to ensure an optimum oxygen level required for the specific specie.

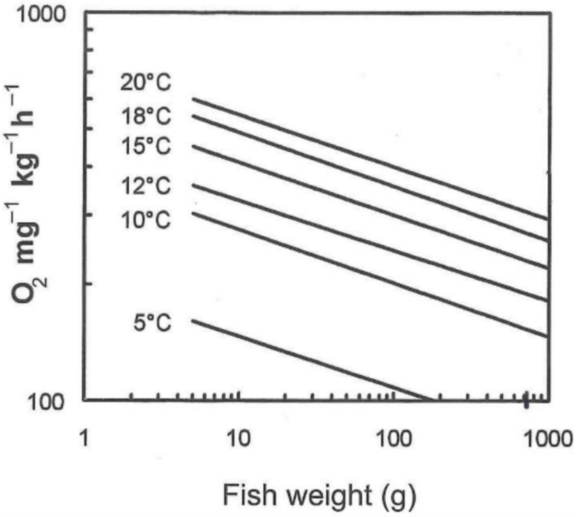


Figure 3.3: Oxygen consumption related to body weight and water temperature (Stead & Laird, 2002).

### 3.3.2 Temperature

Next to dissolved oxygen, the temperature is decisive for production. The temperature does, besides affecting the fish directly, also impact the economic viability of a production system. You can have a perfect rearing environment, but if the temperature is out of optimum range the production will suffer. When it comes to fish farming, it is common to divide the fish into three classifications related to their temperature preferences.

- Cold-water (15°C)
- Cool-water (15-20°C)
- Warm-water (20+°C)

These temperatures are not exact definitions and there will be great variation between species. Atlantic salmon has optimum temperature at 15°C, while Brown trout prefers temperatures between 12 and 14°C (Aston, 1981). Atlantic salmon is classified as cold-blooded, meaning it's body temperature is more or less the same as the water temperature. Being able to control and maintain a stable temperature is important when optimising the growth rate in a production system. Too high temperatures, above optimum, will require more energy for food conversion and the food conversion ratio will decrease (Timmons et al., 2010). Marine Harvest operate with an optimum temperature range between 8 and 14°C for Atlantic salmon, as seen in figure 3.4 (Marine Harvest, 2016).

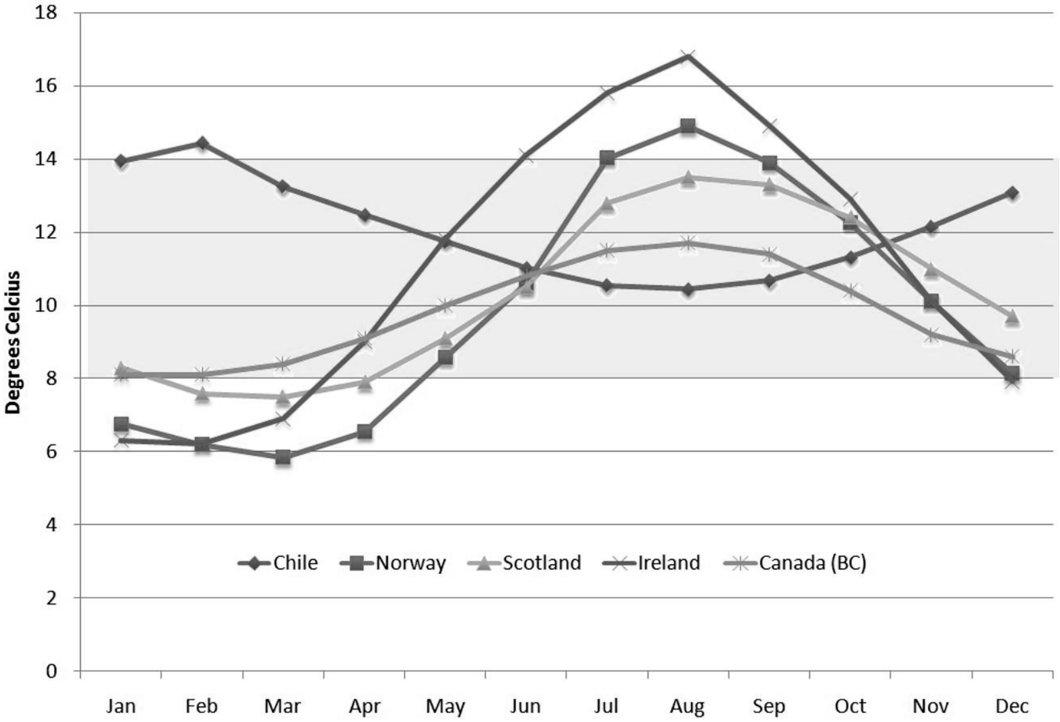


Figure 3.4: Optimum temperature range and approximated temperature profiles for different Salmon producing countries (Marine Harvest, 2016).

### 3.3.3 Carbon dioxide

Carbon dioxide in the water is mainly produced by fish respiration, in addition to decomposition of organic matter. High concentrations of carbon dioxide in the water column reduces respiration efficiency while the tolerance to low dissolved oxygen concentrations decreases. Besides affecting the water column, high carbon dioxide concentrations also affect the fish physiology, decreasing the carbon dioxide release through the fish gills and by that increase the carbon dioxide concentrations in the blood. The fish can then go into respiratory acidosis because of blood plasma pH is lowered. In this condition, the carrying oxygen capacity of hemoglobin is reduced, even if the dissolved oxygen concentration is high. Causing respiration distress (Timmons et al., 2010).

### 3.3.4 Total suspended solids

Total suspended solids are usually a combination of feed, feces and algae. The common definition of TSS and the definition Lekang (2007) uses are:

> *Total suspended solids are defined as the amount of particles stopped by a special fibre-glass filter with pore size of 0.45 [μm].*

It has been reported that fish produce 0.3-0.4 kg TSS for every 1 kg of feed fed. The amount of TSS will effect every aspect of the system downstream. In freshwater the limits for TSS are 25 [mg TSS/L], but 10 [mg TSS/L] are usually the recommended upper limit for maintaining a good operation (Timmons et al., 2010). A high TSS value in the intake water will make disinfection and treatment more difficult and require a highly functioning system. Particles in the water can hide harmful bacteria and increase the risk of disease in the rearing tank. TSS is an important parameter to monitor as mentioned by Svåsand et al. (2016) in table 3.4.

## 3.4 Stocking density

Producing fish in large circular tanks has shown to reduce cost compared to smaller units (Timmons et al., 2010). An important factor, mentioned in table 3.4, is the stocking density. Research by Calabrese et al. (2017) indicates that there is possible to increase the density in certain weight ranges without compromising on fish health and welfare. These studies are important for S-CCS, due to the relationship between stocking density and economic profitability of these systems. Density also affect many other parameters in production, like oxygen needs, removal of $CO_2$ and TSS level (Timmons et al., 2010). These parameters combined with many other are governing for the design of systems and it is therefore important to know the maximum density capacity.

# Chapter 4

# Treatment of intake water

Treatment of intake water to Atlantic salmon production in semi-closed and closed systems can be essential because of the risk of getting pathogenic bacteria into the system could potentially be extremely harmfull for production. Terjesen (2017) identified some of the main challenges related to S-CCS, where treatment of intake seawater was one of the headers.

- Still lack of knowledge about the fish's requirements
- Systems that are robust and reliable to handle higher densities
- Reliable constructions in sea
- Treatment of intake seawater
- Compilation, dewatering and utilization of salty sludge
- Hydrodynamics in huge tanks (>3000 $m^3$)

(Terjesen, 2017)

Production of salmon in semi-closed and closed systems require total control of water quality, and treatment of intake water is a way of optimizing water quality going in to the rearing environment (Terjesen et al., 2013). Water quality in the tanks are mainly determined by metabolites produced and secreted by the fish and the extent to which these metabolites are removed from the tank. Hydraulic retention time (HRT) related to water flow and velocity are important parameters to ensure removal of the metabolites in the tank.

High turnover rate of water and seasonal fluctuations in seawater quality results in change of the environmental load for the microbial community in S-CCS floating in sea. Temperature, light, organic- and nutrient load will change with time and this can be critical for the fish welfare in the system (Rud et al., 2016). Upwelling of sediments from the seabed is another issue that can contribute to unstable microbial community in the rearing environment. Blackwell and Oliver (2008) and Shikuma and Hadfield (2010) found that seabed sediments may contain pathogenic species, and Colwell and Morita (1964) and Urakawa, Kita-Tsukamoto, Steven, Ohwada, and

Colwell (1998) found sediments harbouring Moritella viscosa bacteria (causing winter ulcers). Next to this there will be periods with algal blooms, potentially being a problem for the S-CCS.

Nylund et al. (2015) found that pancreas disease (PD), heart and skeletal muscle inflammation (HSMI) and cardiac myopathy syndrome (CMS) associated with their respective viruses, to be the major diseases expected to be a risk in S-CCS. Skin ulcers caused by Moritella viscosa and gill diseases where also mentioned to be of major concerns as seen in table 4.1 (Nylund et al., 2015).

Table 4.1: Diseases most likely to be of concern when producing in S-CCS (Nylund et al., 2015).

| Potential diseases expected in a S-CCS | |
|---|---|
| Pancreas disease | (PD) |
| Heart and skeletal muscle inflammation | (HSMI) |
| Cardiac myopathy syndrome | (CMS) |
| Ameobic gill disease | (AGD) |
| Moritella viscosa | (Causing skin ulcers) |

Kristoffersen, Viljugrein, Kongtorp, Brun, and Jansen (n.d.) suggested that smolt released in autumn seems to be more exposed to PD infection due to the seasonal fluctuations in the environmental state.

Size of microparasites differ a lot and ranging in a wide specter, from Noda virus at approximately 30 [nm] in diameter (Qian et al., 2003), to IPN virus at 60 [nm] (Nylund et al., 2015). The amoeba, *Paramoeba perurans*, causing the AGD is 20-30 [$\mu$ m] in diameter (Karlsbakk et al., 2013). This range of size indicates that there must be other measures than a mechanical filter to remove these potentially dangerous pathogen microorganisms.

Sea lice, *Lepeophtheirus salmonis*, depending on the life stage vary in size from 45 [$\mu$m] up to 700 [$\mu$m] in the stages before it attacks the salmon to feed and grow bigger (Parsons & Sayavong, 2010). Hence, sea lice can theoretically be, based on size, filtered and stopped before entering S-CCS.

## 4.1 Treatment goals

The main goal for water treatment is to ensure safe production and good fish welfare by removing and neutralizing potential threats present in the water, mentioned here in chapter 4. To ensure this the regulations concerning disinfection of intake water and effluent from land based aquaculture-related activities are as follows (For-1997-02-20-192, 1997):

> ***§9 Pre-treatment of intake water and wastewater***
> *Intake water for aquaculture should be filtered through screening with pore-size* $\leq 0.3mm$.

> ***§10 Requirements for methods of disinfection of intake water and wastewater***
> *For intake water for aquaculture establishments engaged in hatching and production of salmonid and other freshwater fish the method applied shall through recognized scientific evidence under relevant experimental conditions (water quality, temperature) demonstrate a minimum of 3 log (99.9 %) inactivation of Aeromonas salmonicida, subsp. salmonicida, and it is shown, or on the basis of dose-response curves for the IPN virus it is considered likely that the infectious salmon anemia virus (*ISAV) also are inactivated accordingly.*
>
> *In Norwegian ISAV translate to ILA virus

As seen in §9 the requirements for filtering intake water is 300 [$\mu$m]. This pore size removes bigger particles, but will not remove bacteria wich is smaller than 300 [$\mu$m]. To achieve the wanted degree of removal there must be a disinfection method present to inactivate bacteria, like Aeromonas salmonicida, subsp. salmonicida. The method applied should have a minimum of 3 log, equal to 99.9%, removal (Lekang, 2013). 3 log removal is also wanted for infectious salmon anemia virus (ISA) (For-1997-02-20-192, 1997). The regulation is shown in §10.

Because semi-closed and closed systems in sea are relatively new in salmon production it is unclear if the production systems will be regulated on basis of the open net cages or if it will be under the regulations of landbased production systems, or maybe a combination (Rosten et al., 2011). It is clear that the laws and regulations for semi-closed and closed systems in sea must be addressed and added to the existing legislation as this development continues.

## 4.2 Treatment methods

Treatment of water to aquaculture is quite similar to drinking-water treatment and wastewater treatment, and apply the same theoretical basis and same treatment technologies. The difference is mainly in the objective of treatment and what we want to achieve, and challenges related to salinity. Formation of disinfection by-products that can be harmfull to the fish is also very important when we look into seawater treatment technologies for aquaculture production.

As mentioned, in section 4.1, the Norwegian regulation require a 3 log removal of both Aeromonas salmonicida and infectious salmon anemia virus (ISA virus) for landbased production. Currently there are no regulatory requirements for disinfection of the inlet or wastewater from S-CCS in the sea (Rosten et al., 2011). Since there has been evidence of bacteria finding its way into the rearing environment (Breck, 2014), producers are now looking at the possibility of treating the inlet water to S-CCS in sea to avoid diseases and pathogenic invasion (Joensen, 2017).

Treatment technologies tested in INTAKE 2016 included use of ozone, drum-filter, UV and AOP using vacuum UV. All where tested using seawater. Different technologies focus on different parts of the treatment process, such as disinfection and particle removal.

### 4.2.1 Ozone

Ozone ($O_3$) has a high oxidizing potential and is an powerful agent to improve water quality. In aquaculture systems ozone is added to inactivate fish pathogens and destroy organic material (Summerfelt, 2003). Production of ozone appears when oxygen molecules separate into atomic oxygen. Ozone is an unstable gas and can be produced in different ways, by electrolysis, radio-chemical reaction by electrical discharge or photo-chemical reaction (Tchobanoglous et al., 2014). In equation 4.1 the transformation from oxygen to ozone is shown.

$$3O_2 + energy = 2O_3 \tag{4.1}$$

To make effective and stable disinfection using ozone in aquaculture it is important to have good control of the ozone generation, transfer into solution, contact time and residuals that can hurt the production downstream (Summerfelt, 2003). Generation is usually done using an electrical discharge and oxygen feed gas instead of air. Since ozone has a half-life of 15 minutes, and then will be converted to oxygen, it must be produced on site (Lekang, 2007).

After generation the ozone must be transferred into the water column. Because of the cost of producing ozone and the low concentration generated, it is important to optimise the transfer to the water. Transfer of ozone in aquaculture purposes is commonly being conducted by liquid phase diffusers that bubble ozone into the solution. If designed correctly the system should achieve a 90% transfer of ozone (Tchobanoglous et al., 2014).

Using ozone to kill microorganisms requires maintaining a certain level of dissolved ozone concentration in the water for the given contact time. The efficiency of the disinfection depends on the product contact time and the ozone residual concentration. Required contact time and ozone residual concentration is dependant on the desired degree of removal. When using ozone in seawater the ozone residual will more or less convert to active bromine, because of the ozone reaction with bromide. This is measured as total residual oxidants (TRO) and will be present in the solution after the ozone disinfection step. Oxidation-reduction potential (ORP) are used to monitor the oxidizing power of ozone and its oxidants, given in millivolts [mV]. ORP provide a continuous monitoring for ozone and measures the oxidizing capacity in the solution using ORP probes. The relationship between ORP levels and total residual oxidants (TRO) are not linear, making it difficult to use ORP as an indicator for TRO concentration (Timmons et al., 2010). Organic matter or antioxidants in the water reduces the ORP (Lekang, 2013).

Ozone treatment can be placed in different stages of a treatment process depending on what kind of system the treatment is a part of. In a recirculating aquaculture system (RAS) there are at least three different ways of using ozone. If ozone is applied before particle removal treatment it is probably meant that the ozone dose used should create a coagulating effect of the particles to increase removal further downstream (Droste, 1997).

Ozone is very unstable in water and the decomposition of ozone is affected by several parameters, like temperature and pH. In water with higher temperature the solubility of ozone decreases and is less stable. When the pH increases, so does the formation of hydroxyl radicals ($HO\bullet$). Increasing pH also makes the ozone decay much faster (Lenntech BV, n.d.).

### 4.2.2 Drum-filter

Removal of particles are important when it comes to water treatment, since the particles can hide bacterias and micro-pathogens, as well reduce the general water quality. High concentrations of particles will reduce growth and can contribute to increased mortality. Removal of particles will also increase the treatment efficiency of other treatment processes, such as UV treatment.

Filter, dependant on the mesh size will stop, and remove particles. In that way it is possible to choose mesh size on the filter dependant on size of the particle you want to remove. Bacteria and viruses vary in size and must be taken into account when designing filtration treatment.

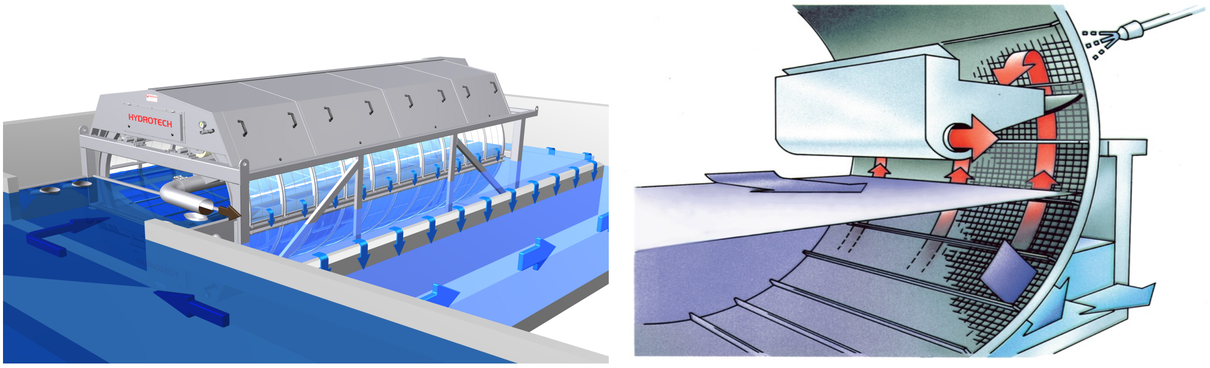
Bigger particles are easier to remove so it is important to handle the flow with it's particles gently before treatment to avoid particles reducing their size. $40\mu m$ can be seen as a lower limit for separating and identifying single particles. There are different principles for removing particles, such as mechanical filtration, depth filtration and settling (Lekang, 2007).

Mechanical filtration means obstructing the water flow to collect particles. Drum-filter is a type of mechanical filter, like the one seen in figure 4.1a. Particles bigger than the pore size will be stopped at the surface of the filter while water will flow through. When particles are collected it is essential that they are removed from the surface to avoid clogging of the system. Clogging of the system will result in head loss and is decreasing the system efficiency. The most common way of cleaning the filter is by back-flushing as seen in figure 4.1b.

In treatment of intake-water the mesh size can be as low as $20\mu m$, because this might also remove some parasites bigger than mesh size, like amoeaba Paramoeba perurans (causing AGD). Decreasing filter mesh size will increase the frequency for changing of filter cloth, exponentially when below $60\mu m$, increasing maintenance (Lekang, 2007).

Depth filtration can be described as a process where water flows through a granular medium, usually sand, to trap particles in the medium. Granular medium can have different size depending on what type and size of particles you want to remove. As for the mechanical filtration there is a need of back flushing to avoid clogging of the system. Depth filtration is not widely applied in aquaculture, but mostly in treatment of potable water and wastewater (Lekang, 2013).

Treatment equipment and filter design are usually specified for a give volume flow to give optimal treatment efficiency, but mechanical filters are normally designed to handle a range of volume flow. Even though, if the flow gets to large and it contains high amounts of TSS the system may fail. Mechanical filtration must be dimensioned to fit the given flow range of the system.



(a) Hydrotech drum filter. (Retrieved 21.03.2017, from: http://www.veoliawatertechnologies.com)

(b) Automated cleaning of a drum filter. (Retrieved 21.03.2017, from: http://www.akvagroup.com)

Figure 4.1: Drumfilter system.

Efficiency of a particle removal system is measured by it's purification efficiency and can be described as follows (Lekang, 2013):

$$C_e = \frac{(C_{in} - C_{out})}{C_{in}} x100 \tag{4.2}$$

$C_e$ = efficiency (%)

$C_{in}$ = concentration of the actual substance entering the filter

$C_{out}$ = concentration of the actual substance exiting the filter

Efficiency can then be represented by TSS removed, or other substances. Phosphorus is a compound that can be removed with particle removal. Up to 80% of phosphorus will be attached to particles, making it a source of interest when it comes to effluent water from aquaculture (Lekang, 2013).

### 4.2.3 UV

UV light has a wavelength between 1 to 400 [nm] and is applied to inactivate bacterias and micro-pathogens (Lekang, 2013). DNA is damaged by absorption of irradiation. Between 190 to 280 [nm] the DNA absorbance is high resulting in an effective disinfection (Timmons et al., 2010). UV light from low pressure low intensity mercury vapour lamps has a wavelength of 253,7 [nm] making them suitable for disinfection purposes. Operating within wavelengths of 250 to 260 [nm] will also contribute to destroy ozone residuals. Inactivation is related to dose and exposure time, where dose is radiation per unit area and might be better described as intensity.

$$D \ = It \tag{4.3}$$

D = Inactivation, UV dose, $[mWs/cm^2]$ or $[mJ/cm^2]$
I = Intensity, $[mW/cm^2]$
t = time, [s]

Effective disinfection with UV depends on lamp intensity, cleanliness of lamp surface, distance between lamp and organisms, age of lamp, type of organism, purity of water and duration of exposure (Lekang, 2007). A rule of thumb is that UV bulbs must be changed at least once a year, sometimes every $6^{th}$ month (Timmons et al., 2010). New systems monitor these things to ensure an effective treatment.

There are mainly three different UV systems operated, presented in table 4.2, low pressure low intensity UV lamps; low pressure high intensity and medium pressure high intensity UV system, where low pressure is most commonly applied. This system gives a monochromatic irradiation specific to 254 [nm]. Medium pressure has a broader spectrum of UV and can operate between 200-415 [nm]. Normally it is required fewer medium pressure bulbs than low pressure bulbs (5-20% of the bulbs), to achieve a given UV dose. On the other hand, the medium pressure UV system will require 2-3 times more power (Summerfelt, 2003).

Table 4.2: UV bulb systems.

| System | Spectre [nm] | Temperature [°C] |
|---|---:|---:|
| Low pressure + low intensity | 254 | 40 |
| Low pressure + high intensity | 254 | 100-150 |
| Medium pressure + high intensity | 200-415 | 600-800 |

A low pressure low intensity system utilize liquid mercury in the bulbs with an optimum temperature at 40°C which controls the mercury vapour pressure. It is important that the lamp remain near the optimum temperature so the mercury does not condense back to its liquid state, since this will decrease the number of mercury atoms available to release photons (Tchobanoglous et al., 2014).

Low pressure high intensity bulbs utilize mercury-indium amalgam instead of liquid mercury, which gives a greater UV output (2 to 10 times). Low pressure high intensity lamps are highly efficient in converting input power into UV light and operates at temperatures between 100-150°C. The amalgam maintain a constant level of mercury atoms, making it more stable over a wider temperature range. UV output of low pressure high intensity lamps can be between 30-100% (Tchobanoglous et al., 2014).

Medium pressure high intensity lamps operate at temperatures between 600-800°C and generate 20-50 times as much UV output than low pressure high intensity lamps. Even so, because of their low efficiency related to power input, they are not so often preferred (Tchobanoglous et al., 2014).

Latest developments in UV disinfection systems are that medium pressure high intensity lamps seems to give better overall treatment as they almost eliminate the problem of microorganisms ≪repairing≫ themselves and continue to reproduce (Atlantium Technologies, 2016).

Radiation dose, retention time and UV transmittance are important parameters when designing a UV treatment system. Usually, in commercial systems, a UV dose of $30 - 40$[mWs/cm$^2$] is enough to get a log 3 disinfection for most of the aquaculture bacterias and viruses. But not all bacterias and viruses will get inactivated, such as Infectious Pancreatic Necrosis (IPN), a virus that demands a much higher dose to get rid off (Lekang, 2007). Liltved, Vogelsang, Modahl, and Dannevig (2006) found that the required UV dose to get a 99.9% reduction of IPN was 246 [mJ/cm$^2$], which is considered to be high in this context.

### 4.2.4 AOP using vacuum UV (V-UV)

Advanced oxidation processes generate hydroxyl radicals (HO•), which is highly capable of oxidizing organic compounds. The dot indicates that there is an unpaired electron in the outer orbital of the molecules. It is because of this that HO• reacts so rapidly with electron-rich organic compounds. For many organic compounds the second order HO• rate constant are $10^8$ to $10^{10}$ [L/mole s], which is much greater than for a lot of other oxidants (Tchobanoglous et al., 2014).

In table 4.3 the oxidation potential for different oxidizing agent are stated. Here we can see that the HO• is one of the most powerful known agents available. Many combinations of treatment methods can be applied to produce HO•, and the most common is the combination of ozone and hydrogen peroxide. UV light and hydrogen peroxide is another method, as well as a combination of all three (Azrague et al., 2012; Huber, Canonica, Park, and Von Gunten, 2003).

An advantage with using AOP is the fact that they produce the hydroxyl radicals at ambient temperature and atmospheric pressure, making design of systems more cost-effective. When designing a new system it is important to consider the quantity of oxidants that are required to destroy the targeted organics (Crittenden et al., 2012).

Table 4.3: Oxidation potential for some selected oxidizing agents. (Lekang, 2013)

| Oxidizing agent | Electrochemical oxidation potential (V) |
|---|---|
| Fluorine (F2) | 3.06 |
| Hydroxyl radical (HO•) | 2.80 |
| Oxygen (atomic) (O) | 2.42 |
| Ozone (O3) | 2.08 |
| Hydrogen peroxide (H2O2) | 1.78 |
| Hypochlorite (ClO-) | 1.49 |
| Chlorine (Cl) | 1.36 |
| Chlorine dioxide (ClO2) | 1.27 |
| Oxygen (molecular) (O2) | 1.23 |

The rate law of HO• reacting with organic compounds are shown here (Crittenden et al., 2012):

$$\frac{dC_R}{dt} = r_R = -k_R C_{HO\bullet} C_R \tag{4.4}$$

$r_R$ = destruction rate of R with HO• radicals, $[mol/L \times s]$

$k_R$ = second-order rate constant for destruction of R with HO• radicals, $[L/mol \times s]$

$C_{HO\bullet}$ = concentration of hydroxyl radical, [mol/L]

$C_R$ = concentration of target organic R, [mol/L]

If concentration of HO• is assumed constant it is possible to calculate the half-life of a targeted organic compound. Usually half-life values and HO• rate constant are given in tables for different organic and inorganic compounds. The half-life equation is obtained by replacing the rate expression with mass balance on a batch reactor completely mixed (Crittenden et al., 2012):

$$t_{\frac{1}{2}} = \frac{ln2}{k_R C_{HO\bullet}} \tag{4.5}$$

$t_{\frac{1}{2}}$ = half-life of organic compound, [s]

There are some major factors affecting an AOP performance, by either absorbing UV light or scavenging HO• radicals. Carbonate species, pH, natural organic matter (NOM), reduced metal ions, reactivity of the parent component with HO• radicals and UV transmittance are all factors that affect the overall performance of the AOP system. Because of this it is important to asses parameters like alkalinity, pH, chemical oxygen demand (COD), total organic carbon(TOC), Ultraviolet transmittance (UVT), iron (Fe) and manganese (Mn) to ensure a highly efficient system.

UV in the range of 100-200 [nm] is called vacuum UV (V-UV). The AOP applied in the experiment emitted UV at 185 [nm] to oxidize strong energy bonds, resulting in direct cleavage of water molecules to create hydroxyl radicals, HO•. Oxidation occurs exclusively by UV lamps, no additional photocatalytic surface are present. The reason is how the bulbs are placed in the reactor, in which a photocatalytic surface can not be assimilated (Mattias Antonsson, Wallenius Water *pers comm*).

$$H_2O \rightarrow H + HO\bullet \tag{4.6}$$

Free radicals production is induced by absorption of 185 [nm] UV-irradiation. Radicals then react with organic and inorganic constituent of organisms, resulting in cell death (Oturan and Aaron, 2014; Maness et al., 1999; Poyatos et al., 2009).

The function of UV light emitted at 254 [nm] is to disinfect, hence inactivate pathogenic microorganisms by damaging photosynthesizing systems, DNA and cell membranes.

## 4.3 Results from experiment

Intake 2016 focused on testing treatment technologies possible to implement in S-CCS floating in sea. This also meant that the water wanted to be tested was seawater. Treatment of seawater can, because of contents of ions like bromide, result in formation of harmfull disinfection by-products. This is important to monitor to ensure that the treated water is safe for the fish. In Intake 2016 the formation of disinfection by-products were monitored by total residual oxidants (TRO) measured in the water before and after treatment.

The relationship between ORP and TRO was shown to be significant, and the concentration of TRO increased with increasing redox potential. Increasing the ozone doses to over 630 [mV] led to a rapid increase of TRO in the water. Interestingly the AOP treatment did not produce any TRO compounds (active bromine) detectable by the DPD method. No degradation effect of UV irradiation on TRO was found.

Another aspect of the results are the treatment efficiency, measured as the degree of removal. In Intake 2016 colony forming units (CFU) were measured before and after treatment to see how well the components performed. CFU is a measure on how many active bacteria that are present in a solution.

Regarding disinfection efficiency, none of the filters reduced the number of bacteria (CFU) under low TSS environment. Under high TSS environment, the number of bacteria even increased after the filtration step. Pre-ozonation seemed to have a positive effect on the removal efficiency of bacteria over the 40 [$\mu$m] filter. For the 300 [$\mu$m] filter, this was not as apparent. The UV, both 40 [mJ/cm$^2$] and 60 [mJ/cm$^2$], and the AOP reduced the amount of bacteria substantially. The reduction was higher when operating under high TSS level, and when including a filter prior to the disinfection step. All the treatments showed a 99.9% reduction, or a 3 - log10 removal, under high TSS environment. Low ozone dose, 300-350 [mV], gave an average reduction of 21% and 48% under low and high TSS environment, respectively, while a high ozone dose, 400-500 [mV], gave a reduction of 67% and 82% under low and high TSS environment, respectively.

The filter reduced the turbidity, TSS and TOC, and reduction was higher over the 40 [$\mu$m] filter compared to the 300 [$\mu$m]. Adding a high dose of ozone prior to the filter did not give a conclusive answer to whether this affected the removal efficiency. Ozonation did not affect the level of UVT, turbidity, TSS and TOC under low TSS environment. Under high TSS environment, the low ozone dose (300-350 mV) led to a slight increase in UVT and a slight reduction in level of turbidity, TSS and TOC. Increasing the ozone dose reduced the turbidity somewhat more.

It is important to monitor the TRO levels, especially when using ozone. Ozone doses must be determined and monitored closely. AOP did not contribute to increased levels of TRO and UV showed no degradation effect of TRO levels. In freshwater UV can operate as a safe-guard to destroy and reduce the TRO, but in seawater this is not the case.

A combination of the different technologies seems to give the desired effect on amount of bacteria. Ozone, filter, UV or AOP alone does not result in a satisfactory effect.

## 4.4 Concerns regarding treatment

Treatment of intake water seems to be necessary and to be a solution to be implemented in the next phase of development in S-CCS (Joensen, 2017). Even so, there might be some issues related to treatment of intake water. A challenge related to S-CCS floating in sea is that the intake water may change characteristics drastically during production. S-CCS are built as flow through systems and seasonal fluctuations may change the microbial community (Rud et al., 2016).

Sanchez-Vizuete, Orgaz, Aymerich, Le Coq, and Briandet (2015) found that microbial biofilms developing in aquaculture tanks could potentially operate as reservoirs for opportunistic pathogens, providing advantages for survival against disinfectants and antibiotics. Potentially this mean, even if the water is disinfected and treated, formation of harmfull bacteria can occur. Attramadal (2017) argue that disinfection in some cases might promote a bacteria community consisting of opportunistic pathogens, which can cause a harmfull environment for the fish over time. This must be investigated further.

# Chapter 5

# Salmon production

Now that S-CCS are presented and described, it is time to investigate how S-CCS, and keeping salmon longer on land, can affect the salmon production in Norway. It is essential that there is a common understanding of how salmon production is conducted today and how the overall production strategy is at the present. That is what we will consider in this chapter.

Besides individual production regimes across companies, there are laws and legislation that regulate the production along the Norwegian coast, and there are also differences in regulations along the coast. Maximum allowed biomass per license for instance. In Troms and Finnmark the maximum allowed biomass is 945 [ton], while it is 780 [ton] in all other parts of the country (Vikingstad, 2016). It is common to use between 3-10 licenses on each site, reaching a total production between 2500 to 10 000 [ton] at one site. As a measure against disease, sea lice and environmental challenges the coast has been divided into zones to synchronize production in regional areas (Iversen et al., 2015). Resulting in joint fallowing within the zones.

In this chapter we will also look into production history and trends. Can the introduction of S-CCS in Atlantic salmon farming change the production regime and benefit Norwegian Atlantic salmon production today?

## 5.1 Production cycle

Producing salmon from egg to market size (4-5 [kg]) takes between two to three years. The first year of production it goes from egg to alevins, fry, parr and ends up as a smolt, ready for a life in sea. During these stages it goes through physical changes and the transformation to smolt is called smoltification (Marine Harvest, 2016). During this process, smoltification, the salmon adapt to a life in seawater and goes through a series of physiological changes (Asche & Bjørndal, 2011).

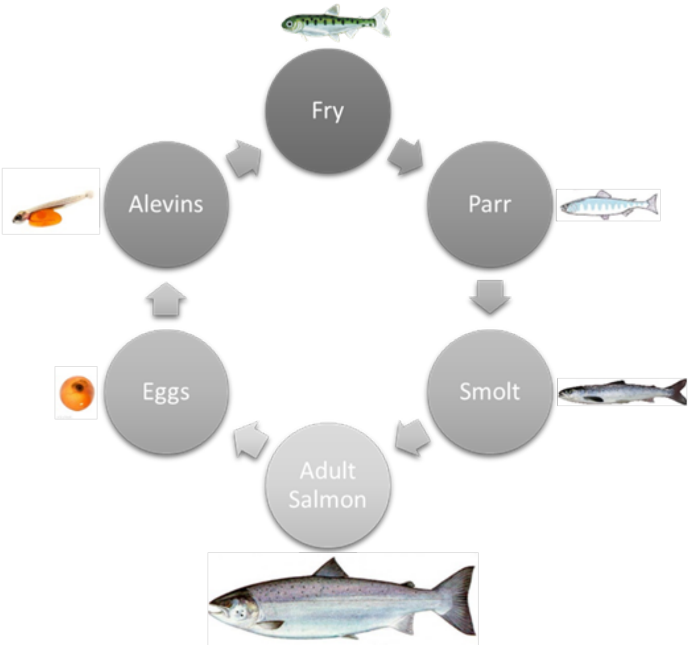


Figure 5.1: Illustration of the life cycle of the Atlantic salmon.

These first stages the fish is reared in freshwater, mainly in landbased production facilities using RAS technology or flow through. Freshwater production takes approximately 12 months. By using light manipulation the producers can accelerate smoltification process up to 6 months (Marine Harvest, 2016). Figure 5.1 illustrates the life cycle stages of Atlantic Salmon from egg to adult.

Total production in sea takes approximately 14-24 months, making the total production length to 24-40 months. It is important to state that production length is very temperature dependant. In Chile for instance, total production cycle can be slightly shorter as the seawater temperatures are more stable in the optimal temperature range (Marine Harvest, 2016). Temperature dependence will also influence production along the Norwegian coast as there are temperature fluctuations along the coast.

Smolt is mainly put into seawater twice a year, in spring and autumn. Harvest volume is usually spread throughout the year, but there are some differences. In figure 5.2 you can see harvesting for each month in 2016. Because of higher growth in the last quarter, due to higher sea-temperature, the harvest quantity is also slightly higher during this period. Figure 5.2 also indicates that the summer months of June and July gets a dip in harvest volume. This is due to the shift in generation, resulting in a larger gap between small and large harvested Atlantic salmon (Marine Harvest, 2016).

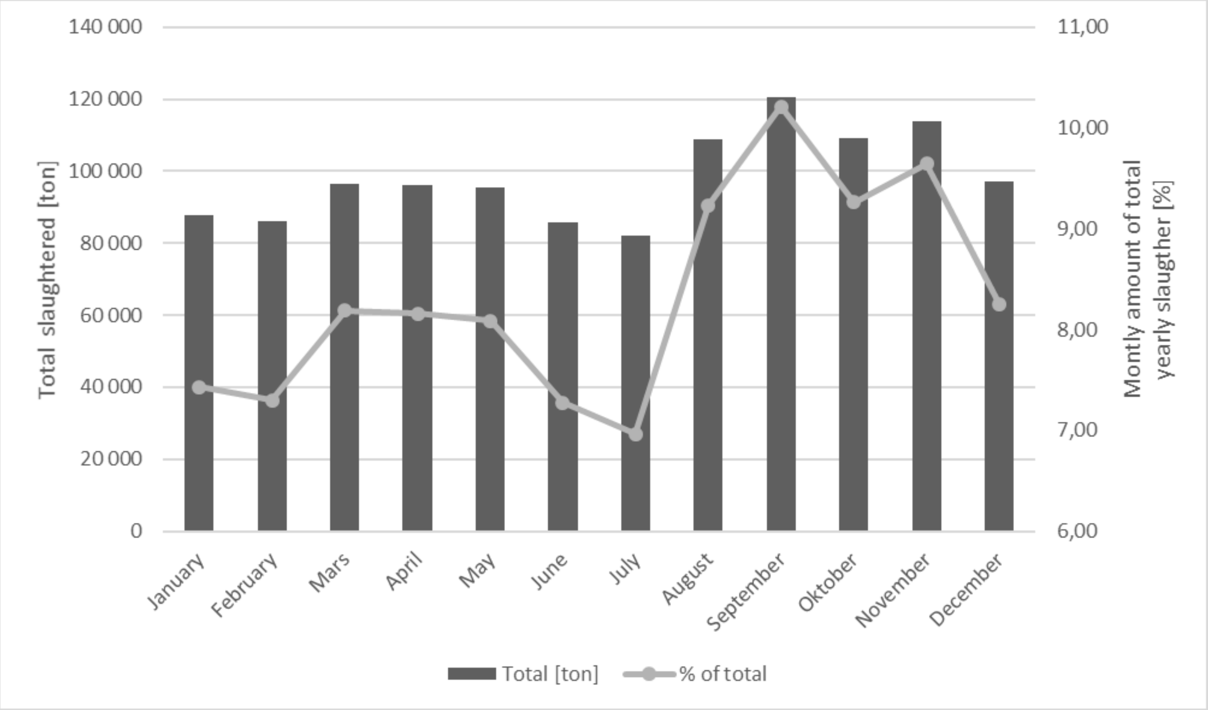


Figure 5.2: Total harvested amount of salmon in Norway throughout the year in 2016. Secondary axis shows the percentage of total for given months.

### 5.1.1 Feed conversion and specific growth rate

Feed utilization is an important factor in aquaculture and one of the arguments to produce in closed and semi-closed systems is the potential ability to reduce the feed conversion ratio (FCR) compared to open net production. Feed conversion can be calculated as follows (Asche & Bjørndal, 2011),

$$\text{FCR} = \frac{\text{kg feed fed}}{\text{kg body weight gain}} \tag{5.1}$$

Body weight gained must be calculated using total biomass for the whole production unit. There are other parameters to consider when talking about feed conversion. Mortality, population sample and actual consumption of feed are all important and make the calculation of FCR more complex. Biological feed conversion rate ($\text{FCR}_b$), equation 5.2, includes the losses in production (Stead & Laird, 2002).

$$\text{FCR}_b = \frac{\text{kg feed fed}}{\text{kg body weight gain} - \text{kg loss}} \tag{5.2}$$

To asses the feed utilization on profitability, the economic feed conversion ratio ($\mathrm{FCR}_e$) is established.

$$\mathrm{FCR}_e = \frac{\text{kg feed fed}}{\text{kg of harvested fish} - \text{kg of smolt}} \tag{5.3}$$

In traditional open net pen production the average FCR is estimated to be 1.17 (Marine Harvest, 2016). Due to the increased control and monitoring in closed and semi-closed systems, combined with high water quality, the FCR could potentially be better than the traditional alternative.

In addition specific growth rate can be of interest since it is related to FCR. It highlight the percentage weight gained per day. If the FCR is known SGR can be found by dividing the percentage body weight fed per day by the FCR.

$$\mathrm{SGR} = 100 * \frac{\ln(\mathrm{W}_f)\text{ - }\ln(\mathrm{W}_i)}{\delta\mathrm{t}} \tag{5.4}$$

$\mathrm{W}_f$ = final weight, [kg]
$\mathrm{W}_i$ = initial weight, [kg]
$\delta$t = time between start and harvest, [days]

Together with temperature, the development in feed and breeding programs are reducing the total production time further. It has been reports that total production time in sea has been down to 10 months (Brundtland & Mathiesen, 2016). Feed conversion ratio and growth are closely related to management of production and required expertise in production. This development together with the new productions systems can be very important for the industry to be able to take control of the rapidly growing production cost.

## 5.2 Licenses, law and regulations

Licences are applied as a tool to regulate establishment and capacity expansion in Norwegian seafood production. The Norwegian Aquaculture law (Aquaculture Act) state the purpose of this regulation (Lov-2005-06-17-79, 2005):

> ***§1 Purpose***
> *The law shall promote the aquaculture industry profitability and competitiveness within the framework of sustainable development and contribute to wealth creation along the coast.*

Licenses are awarded in licensing rounds with the purpose of spreading the ownership in the industry, develop coastal communities and secure production in a wide geographical range along the coast (Iversen et al., 2015). The green licence allocation in 2013 demanded implementation of new technology as a competitive criterion. Together with this was an acceptance and understanding of a more stricter sea lice policy towards the new licences granted.

Sea lice is a huge contributor to the growing cost and with a stricter sea lice policy for the new green licenses it is implied that new design and technology concepts must focus on preventive measures to avoid sea lice infestations.

In 2015 the Directorate of fisheries allowed for a license extension meaning license-owners were allowed to increase the MTB with 5% by a one million NOK consideration. Accepting this also meant to introduce a stricter sea lice policy, lowering the acceptance level to 0.2 full grown female sea lice per salmon (For-2015-06-17-817, 2015). Later that year, in November, the Directorate of fisheries presented developing licenses to help develop technology that can solve environmental and area related challenges that the industry faces (Fiskeridirektoratet, 2016b).

Minister of fisheries in Norway at that time, Elisabeth Aspaker said (Fiskeridepartementet, 2015):

> *We are currently making it possible for the big projects that involve both significant innovation and significant investment, and not at least some risk of failure, to see the light of day. If they succeed, the entire industry could benefit from the knowledge provided by the projects.*

Development licenses are allocated free of charge, if application is approved, for up to 15 years and if the project is implemented in accordance with the objectives set, the permissions may be converted to commercial licenses for a compensation of 10 [million NOK] (Fiskeridepartementet, 2015).

The latest changes in regulation and licenses as mentioned above is a major contributor to the development of S-CCS and landbased farming as it requires large investments and meet the demand of technological and biological improvement.

Even though there has been updates in the law and regulation it is still unknown how the Directorate of fisheries will regulate production systems like S-CCS floating in sea. Because of this there has been made assumptions regarding possible challenges related to regulations for S-CCS in chapter 6 and 7.

## 5.3 Production history and trends

Over the last couple of decades salmon production in Norway has evolved from being a small scale, low technological and often family-owned industry, to become a huge and industrialized industry with bigger companies taking charge of the development.

Large investments seems to be a necessity when it comes to developing salmon aquaculture industry in Norway further. The concepts evolving requires a lot of investment just to be tested and it requires more specific expertise in the industry. Another reason for seeing this development over the last years, can be seen in figure 5.3. The trend over the last decades has been acquisitions and companies merging to become larger and more competitive. This industry structure, with fewer, but larger companies can be an advantage when committing to huge, costly and resource demanding projects.

In 2015 it was produced 1.3 million ton Atlantic salmon in Norway, and in 2016 the export of Atlantic salmon reached 61.3 billion NOK. Approximately 3 500 open net pens were in production on average each month in 2016, at 800 sites across the coast (Steinset, 2017). These numbers make the salmon industry one of the biggest contributor to growth in Norwegian industry at the moment.

No significant increase in production volume over the last five years together with an increase in production cost [NOK/kg] has been saved by a consistently high salmon-price. A continuously and steady increase in production cost in the years to come can be crucial, probably not for todays traditional production level, but most certainly for the possibility of growth and expansion. Figure 5.4 indicates that there has been a significant increase in production cost from year 2012. To be specific, it has been a 32% increase in production cost from 2012 to 2015 (Fiskeridirektoratet, 2016a).

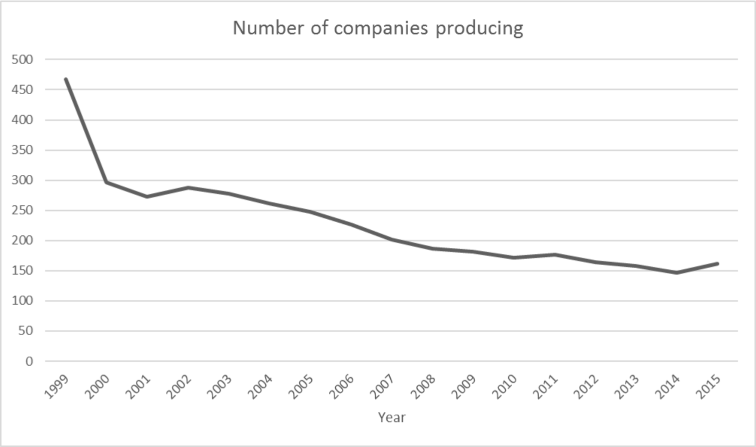


Figure 5.3: Number of companies producing Atlantic salmon in Norway. There has been a significant decrease in number of companies (Steinset, 2017).

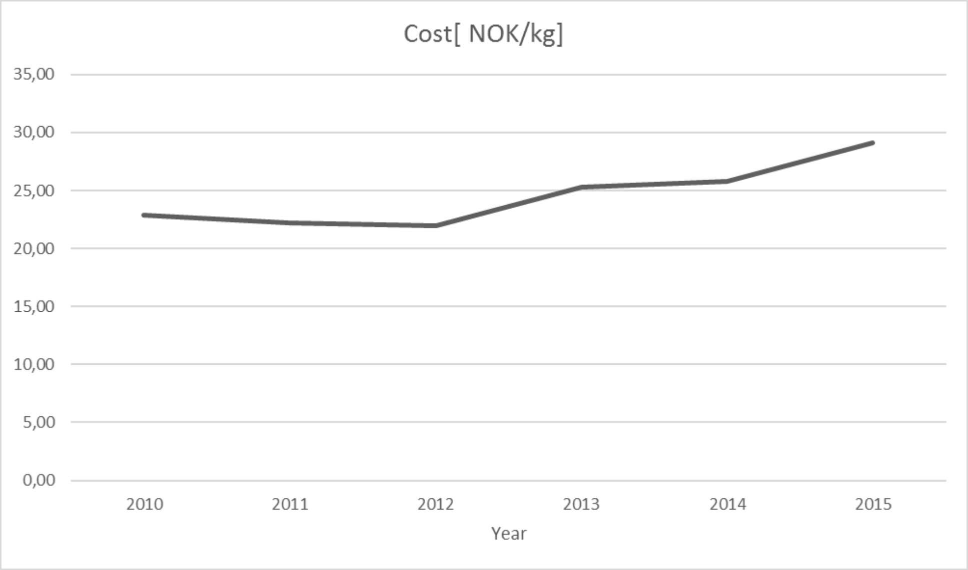


Figure 5.4: Development of production cost from 2010 to 2015 (Fiskeridirektoratet, 2016a).

Traditional production in open net pens has been, and still is, a cost effective way of producing Atlantic salmon along the Norwegian coast (Liu et al., 2016). Utilizing the natural coastal currents and sheltered coast line combined with stable temperature profiles and good water quality in general. As the production cost increases because of increase in operations and handling of fish, the traditional production system loose competitive strength and can be threatened. Sea lice, diseases and environmental impacts are all contributors to increasing number of operations and handling. In table 5.1 production cost is divided into sub-groups to easier see what has been affecting the increase during the last years (Fiskeridirektoratet, 2016a). Smolt cost has increased by 11% and is mainly due to the introduction of bigger smolt, before put into sea production. Even though this expense has increased it might be a important contributor to reducing total production cost (Iversen et al., 2015).

Table 5.1: Other operating expenses has increased significantly (Fiskeridirektoratet, 2016a).

| [per kg] | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Change [%] |
|---|---|---|---|---|---|---|---|
| Smolt | 2.45 | 2.27 | 2.16 | 2.19 | 2.52 | 2.72 | 11 |
| Feed | 10.98 | 11.00 | 10.85 | 11.50 | 11.83 | 13.18 | 20 |
| Insurance | 0.15 | 0.14 | 0.12 | 0.11 | 0.10 | 0.13 | -18 |
| Salary | 1.69 | 1.60 | 1.55 | 1.80 | 1.92 | 2.07 | 22 |
| Depreciations | 1.16 | 1.09 | 1.15 | 1.23 | 1.26 | 1.58 | 36 |
| Other operating expenses | 3.30 | 3.36 | 3.26 | 5.58 | 5.54 | 6.31 | 91 |
| Net financial expense | 0.29 | 0.19 | 0.22 | 0.28 | 0.20 | 0.16 | -46 |
| Production | 20.03 | 19.66 | 19.31 | 22.69 | 23.38 | 26.15 | 31 |
| + Slaugther | 2.84 | 2.52 | 2.67 | 2.64 | 2.46 | 2.95 | 4 |
| Total cost | 22.87 | 22.18 | 21.98 | 25.33 | 25.83 | 29.10 | 27 |

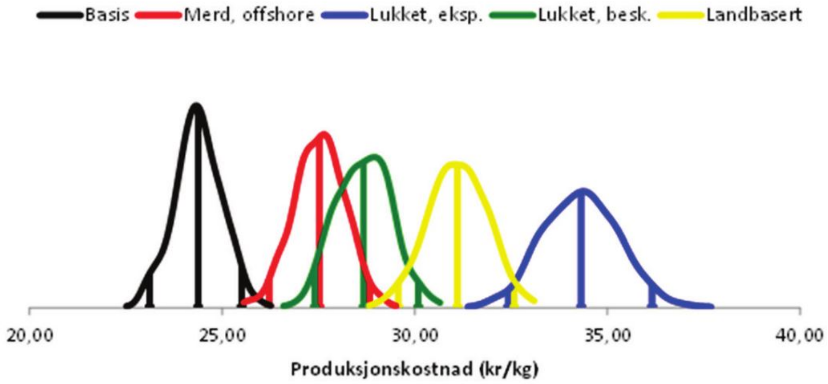


Figure 5.5: Probability distribution for production cost in different production systems (Iversen, Andreassen, Hermansen, Larsen, & Terjesen, 2013). The black graph is traditional open net pen production, exposed farming is red, landbased production is yellow and the green graph is production in semi-closed containment system.

Iversen et al. (2013) presented figure 5.5 in their report and as observed the production cost difference between traditional open net pens and S-CCS was quite large at that time. Iversen et al. (2013) estimated production cost for traditional open net pen to be in the same range as statistics from Fiskeridirektoratet (2016a), based on real data.

All of these mentioned trends can be seen as underlying arguments, drivers and motivation to develop alternative production strategies. To move the total production onshore or to produce the total volume in S-CCS floating in sea seems unrealistic, but to split the production and utilize these systems in some parts of the production can be valuable (Mathisen, 2016).

## 5.4 Landbased aquaculture in Norway

Production of smolt in landbased production systems has been around for many years, but the last decade there has been a development regarding the technology used in this systems. Today almost every new built landbased systems is using RAS technology and many existing landbased smolt production systems have changed from flow-through technology (FT) to RAS.

RAS reuse up to 99.9% of the water where it is treated by applying different treatment technologies to give optimal rearing environment for the specie farmed (Bregnballe, 2015). A general RAS setup consist of mechanical filtration, biofilter, degasser, oxygen enrichment and disinfection, similar to the technologies tested in Intake 2016. These treatments remove waste excreted by the fish, adds oxygen and keep the water parameters in the optimal range. Figure 5.6 depict an example of a RAS facility.

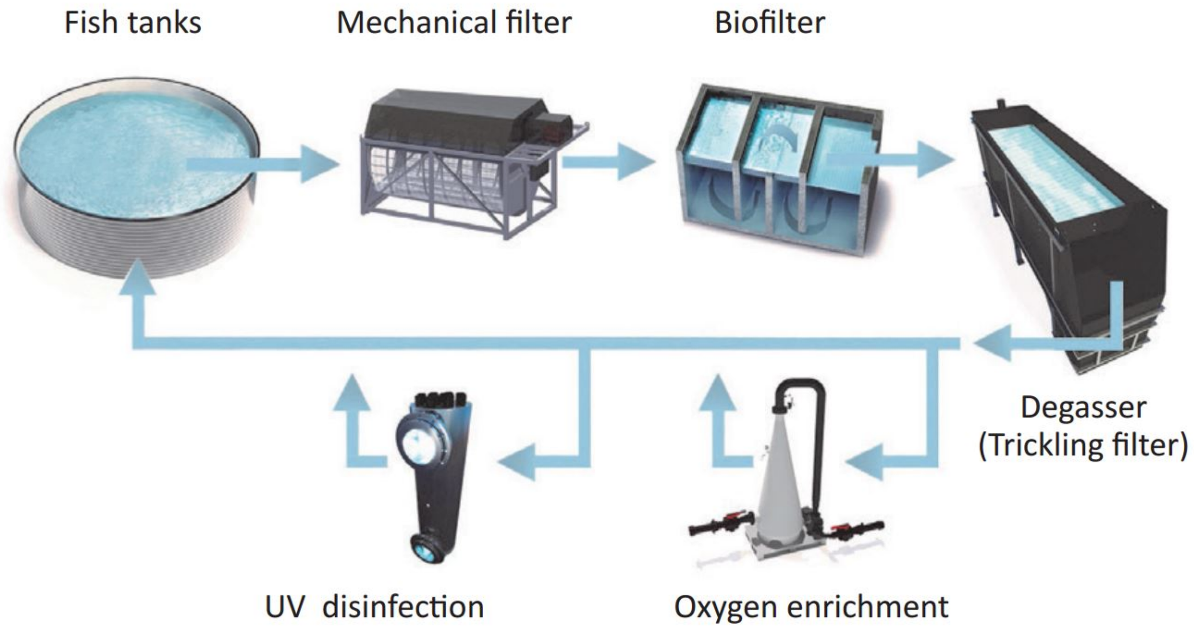


Figure 5.6: Example of a RAS setup. Other technologies can be added to the system if required, like ozonation and denitrification. (Bregnballe, 2015)

Landbased aquaculture allows for even greater control on the rearing environment than the S-CCS floating in sea. Landbased production of Atlantic salmon up to market size is yet to be documented as economically success, but it has been shown to be possible. In this study the opportunity of producing postsmolt up to one kilogram in landbased RAS facilities are evaluated in one of the production strategies proposed.

Production of Atlantic up to market size in landbased production facilities are on the door step reaching commercial scale (Davidson et al., 2016; Nordic Aquafarms, n.d.). This development are also emerging as a potential solution to all the challenges presented.

## Part III

# New production strategies

# Chapter 6

# Criteria

In this chapter different strategies of implementing S-CCS into todays production regime will be introduced along with the motivation and arguments for implementing them as well as the criteria they will be assessed on.

## 6.1 Motivation for development and new technological solutions

In earlier chapters some main drivers for developing the production systems has been introduced. Increase of production cost due to sea lice and diseases seems to be the main contributor as well as the possibly negatively effect Atlantic salmon production can have on the coastal environment (Bergheim, 2010). Another important driver for innovation and development is the lack of optimal space to produce Atlantic salmon along the coast, resulting in less effective production on some sites (Kystdepartementet, 2011).

Isaksen, Andreassen, and Robertsen (2012) found that stricter requirements for sites and site structure, combined with a more restrictive attitude towards allocating area for farming in municipalities makes access to good sites more difficult. 63% of breeders says access to good sites is their biggest challenge (Hersoug, Andreassen, Johnsen, & Robertsen, 2014).

Demanding production conditions are mainly due to sealice and diseases (Svåsand et al., 2016), increasing the need for operations and handling of the fish, resulting in higher production cost (Iversen et al., 2015). In light of this there are also companies who want to have the whole production on land, all the way until market size (Davidson et al., 2016; Nordic Aquafarms, n.d.).

Low mortality is a key to success when it comes to production of Atlantic salmon. Bleie and Skrudland (2014) reported that the registered mortality in sea production was 16.3% for Atlantic salmon. This indicates a much higher mortality than desired. Approximately 80% of fish produced in sea in Norway were included in the survey published in 2014.

In search of increasing production volume S-CCS stands out as a way of complementing the existing structure of Atlantic salmon production, increase efficiency and to eliminate some of the challenges, rather than being a direct contributor to large increase in total production volume. Concepts of ocean farming in huge offshore structures like SalMars Ocean Farming (Salmar, n.d.), seems to be more specifically focused on increasing volume. Combining new production systems can also be interesting to look into, but we will focus on the possibilities of implementing S-CCS into todays production regime. These factors combined with technology development in water purification specific to aquaculture provide increased focus on development of new and unorthodox production designs.

## 6.2 Assumptions and requirements for S-CCS

Before trying to compare different strategies and estimate important data, like production volume, system capacity, efficiency and production time, some assumptions must be made. Since there are mostly new and few research-papers backing up these assumptions, it is difficult to get exact and validated data. To do the calculations and be able to compare strategies for S-CCS these assumptions are made:

- The limit of 200 000 fish in a open net cage is not applicable when it comes to S-CCS
- Density limits can be, as long as fish welfare and health are preserved, increased up to 75 kg/m$^3$
- Production time for given size-ranges documented in full scale research testing will be used to assume production time
- Fish welfare and health are cared for
- Temperature in sea set to be 10°C for estimation of production
- Time exposed in sea will, for simplification, be linear to the risk of getting sea lice and diseases. Meaning seasonal fluctuations and local environment differences will not be accounted for

## 6.3 Criterion I: Reducing time exposed in sea

Traditional production time in sea is approximately 14-24 months (Marine Harvest, 2016). Reducing the time Atlantic salmon is exposed in open net pens can reduce the risk of contaminated water bringing diseases and sea lice into the rearing environment. Reducing time exposed in sea can be said to be linear to the potential of getting infections and diseases, but this not entirely correct as sea lice, diseases and infections are affected by many parameters, like temperature, density, seasonal fluctuations and water exchange (Rud et al., 2016).

As important as reducing time in sea, is the knowledge of knowing when you should produce in sea and when you definitely should not. This is dependant on site specifications and seasonal fluctuations. Historical data from BarentsWatch Norwegian fish health combined with sea lice pressure models from Institute of Marine Research can be used to predict when sites should be fallowed and when it should be in production. Experience are an important factor when deciding when to produce on given locations and must be taken into account.

Reducing production time in open net pens will reduce amount of individuals in sea because of the maximum allowed biomass restrictions. At the same time it will be fewer sea lice generations affecting the Atlantic salmon during it's life cycle, resulting in a possible reduction of sea lice (Iversen et al., 2013).

### 6.3.1 Postsmolt

Producing postsmolt in S-CCS has been proposed lately (Terjesen, 2014). Most research and development related to S-CCS are focusing on the possibility to produce postsmolt in these systems before transporting them into open net pens for the grow out phase. Small smolt has shown weakness when transferred to sea and producing a bigger smolt can give a more robust fish to handle the transfer better (Iversen et al., 2013). Producing postsmolt in S-CCS can, if water quality and rearing environment are optimal, reduce the production time from 0.2 gram to 1 kilogram as well. With how much is difficult to specify since it has not been done in commercial production yet. Tests have proven that S-CCS shows similar or better growth rates compared to traditional open net production (F. Nilsen, 2017; Handeland et al., 2015). If the prototype-testing is an indicator it is possible to reduce the production time and this can be seen as a bonus in addition to reducing time exposed in sea.

These factors combined makes postsmolt production in S-CCS in sea interesting. Producing postsmolt in landbased production facilities has also been proposed by some, but the necessary investments and volume upgrades needed on todays landbased smolt production facilities seems to be too large (Mathisen, 2016).

### 6.3.2 Big fish - close to market size

Big fish means Atlantic salmon close to market size, around 3-4 kg. Keeping fish close to market size in S-CCS can be another way of reducing the time exposed in sea. Operations, like delousing, crowding and moving of fish, are major contributors to the growing production cost and the most expensive operations are involving big Atlantic salmon, close to market size. If it is possible to reduce the amount of operations on Atlantic salmon close to market size, it could impact the production cost. This has not been discussed so much as the postsmolt strategy, but different actors have proposed ideas similar to this on conferences and workshops (Joensen, 2017). Both post-smolt and big-fish strategies contribute to reduce time exposed in sea.

## 6.4 Criterion II: Mortality

High mortality rates are also one of the major concerns in todays production, as a result of the increase in operations, handling and more intensified production. Another aspect is that small smolt are found to handle the transfer to sea worse than larger smolt (Ytrestøyl et al., 2014), increasing mortality related to transfer. Producing bigger smolt before being put into the sea phase could contribute to reducing mortality.

Marine Harvests CEO Alf-Helge Aarskog emphasize that there has been development in vaccination, feed, genetic material, improved smoltification tests and sites during the last decades. Still the mortality is worse today than in 1993 and 1994 (M. Pettersen, 2017). Mortality is not only a indicator of poor animal welfare (Jansen et al., 2016), but an economic loss for the producer. If we assume that the average weight of dead-fish to be one kilogram we can estimate the economic loss of the industry in total in 2016. Assuming that the dead-fish would have been produced up to five kilogram, the losses are significant.

If we only look at the potential for income, the losses are huge, approximately 10 billion NOK for fish at five kilogram. If S-CCS can reduce the total mortality it can improve both fish welfare and the economy for the producer substantially.

Sea lice and operations regarding sea lice infestations are also related to mortality, but variation in delousing, sites and fish welfare makes it difficult to give exact data (Holan et al., 2017). It can be difficult to relate mortality after delousing directly to the operation itself. The fish could have been infected by disease before the operation resulting in a higher mortality than if the fish was disease-free. These things are difficult to confirm, but Jansen et al. (2016) indicate that operations like delousing affect the mortality considerably. Especially methods involving physical handling of the fish.

Table 6.1: Total of dead-fish and the losses related to mortality in 2016 (Fiskeridirektoratet, 2016a). Assuming average weight of dead-fish in sea phase to be one kilogram. The average has increased the last years, causing concerns as it is expensive to lose bigger fish (J. Pettersen, 2017). Assumed production cost of 30 [NOK/kg] and Atlantic salmon price of 40 [NOK/kg]. This assumed price is actual too low as the average price for five kilogram Atlantic salmon throughout 2016 was approximately 60 [NOK/kg]. Resulting in a actual higher loss of potential income.

| **Weight** [kg] | **Total** [in 1000] | **Total amount** [kg] | **Price** [NOK/kg] | **Prod. cost** [NOK/kg] | **Lost profit** [B NOK] |
|---:|---:|---:|---:|---:|---:|
| 1 | 48 300 | 48 300 000 | 40 | 30 | 0,5 |
| 5 | 48 300 | 241 600 000 | 40 | 30 | 2 |

Operations and handling of fish sometimes includes a starvation period which basically means stop in production. When fish is starved they loose body-weight instead of gaining, which is a loss for the producers. Rødseth (2016) describes this to be a significant economic loss for the producers. They calculated 100 000 ton in loss only related to starvation before delousing. This affect total production volume, either in lower harvest sizes or longer production time, and is an economic loss for the producers.

If mortality decrease as a result of implementing S-CCS the volume gained because of this will increase the total volume. If mortality data from 2016 should be halved it would increase volume with 120 000 ton, which account for approximately 10% of total production in 2016. The possibility to reduce the total mortality with 50% can be seen as very optimistic.

F. Nilsen (2017) and Handeland et al. (2015) both presented results of high survival rates in S-CCS, but it also showed that there are differences between the systems designed. Assuming that there is possible to achieve a survival rate of 99% in S-CCS, when producing at optimal conditions, will affect the mortality.

## 6.5 Criterion III: Cost

Cost in this study is investment cost related to the S-CCS units. Iversen et al. (2013) calculated that investment cost for S-CCS would be around 2 500 [NOK/m$^3$]. In lack of other sources related to the cost of S-CCS, this estimation is used in this study as well.

In the analyse Neptun are used as example, so cost is closely related to the number of units needed in the strategy. The strategies are all including the total production of Atlantic salmon in Norway and production data from 2015 and 2016 are retrieved from SSB and Directorate of fisheries. This forms the basis for calculating the cost.

## 6.6 Criterion IV :Efficiency

S-CCS in sea could be a potential contributor to increased efficiency of traditional sea sites, but it will depend on the regulations, licenses, production volume and how the system will be applied in production. Volume of production units are an important factor. As seen in figure 6.1, most of the systems being tested today are smaller units and it seems it is only Neptun that has the volume and capacity to become a contributor to affect production volume. The other concepts would demand too many units and sites to contribute to growth in total production volume as seen today.

By applying smolt of varying size and transfer smolt to sea at different times throughout the year, it could be possible to produce closer to the maximum allowed biomass limit at each site, compared with two groups of smaller smolt as todays practice (Iversen et al., 2013). Efficiency in this case can be seen as how many production cycles in open net pens that theoretically can be produced by introducing S-CCS and landbased postsmolt production, compared to todays production regime with average cycle of 18 months in sea (Marine Harvest, 2016).

When discussing volume and efficiency in new production strategies it is important to take into account the relationship and interaction between traditional open net pens and S-CCS in sea. If S-CCS are to be a part of the production chain it must be fitted to the existing production regime. If a produced amount of postsmolt from a S-CCS are to be transferred to open net pens it must be a ratio so it will make both systems efficient and producing up to optimal and maximum allowed biomass.

Increasing production time in closed and semi-closed systems in sea and on land can affect the efficiency of open net production sites. If it is possible to get a higher turnover in the open net pen production systems they can be able to produce more cycles than today. This can be, as Mathisen (2016) presented, limited by the law and regulations related to biomass. In this analysis the efficiency is measured as how many more production cycles it is possible to produce in a open net pen system compared to todays production strategy.

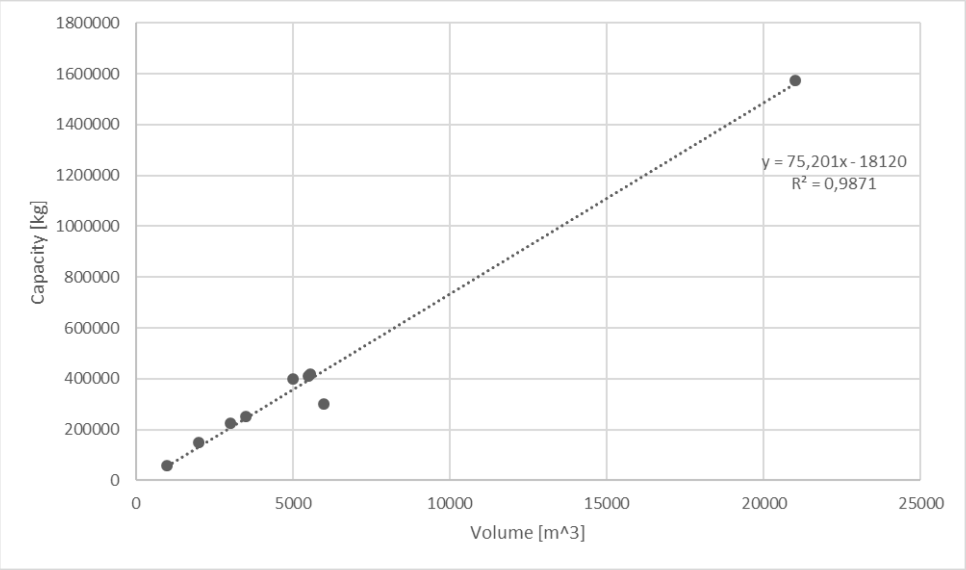


Figure 6.1: Capacity and volume plotted for some of the S-CCS concepts being tested. When density is not given it is assumed to be 75 [kg/m$^3$] as proposed by Calabrese et al. (2017). The Neptun concept stands out, being the biggest S-CCS in sea so far.

## 6.7 Criterion V: Sites and area

Sites and area are also highly dependant on the the volume of S-CCS and fish density allowed (Henriksen, Terjesen, Rosten, Winther, & Ulgenes, 2012). As seen in figure 6.1 volume of todays S-CCS are much smaller than a traditional open net pen, suggesting that there must be a bigger occupation of area to be able to produce the same amount as today with S-CCS, since more units are needed (Rosten et al., 2011: Henriksen et al., 2012). A traditional open net pen has a volume of 50 000 to 100 000 [$m^3$], compared to the S-CCS shown in figure 6.1, which is mostly around 3000 to 5000 [$m^3$]. Increasing maximum fish density allowed combined with bigger volume in the S-CCS, like Neptun at 21 000 [$m^3$], can help reduce the area demand.

Possibly high environmental loads, like waves and currents, on the systems might require a stronger mooring and anchoring system which can increase demand of seabed area. Some of the prototypes tested has shown weakness related to storms and high environmental loads. Making an enclosing environment affect the hydrodynamic relationship between the internal and external environment and sloshing can be a challenge. Sloshing occur when a tank filled with water are being exposed to forces when floating in water, resulting in possibly higher internal waves inside the tank, than the external waves (Faltinsen, 2009). These hydrodynamic forces and challenges are important to understand and further research on hydrodynamics in these systems are needed.

Because of the hydrodynamic challenges it is most likely that S-CCS will demand sites closer to land to ensure shielded and safe operations, and by that closer to communities, houses and people. This might be a problem and create conflicts related to outdoor recreation and peoples home and cabins. On the other hand moving more production into sheltered areas can reduce the conflict with fishing industry. Either way, it must be expected that a change in production may create area conflicts.

In this analyse Sites and area are measured as how many S-CCS units each strategy will need, compared to each other. Since producing in S-CCS will require more units than todays traditional production regime, the strategies are not compared to traditional production.

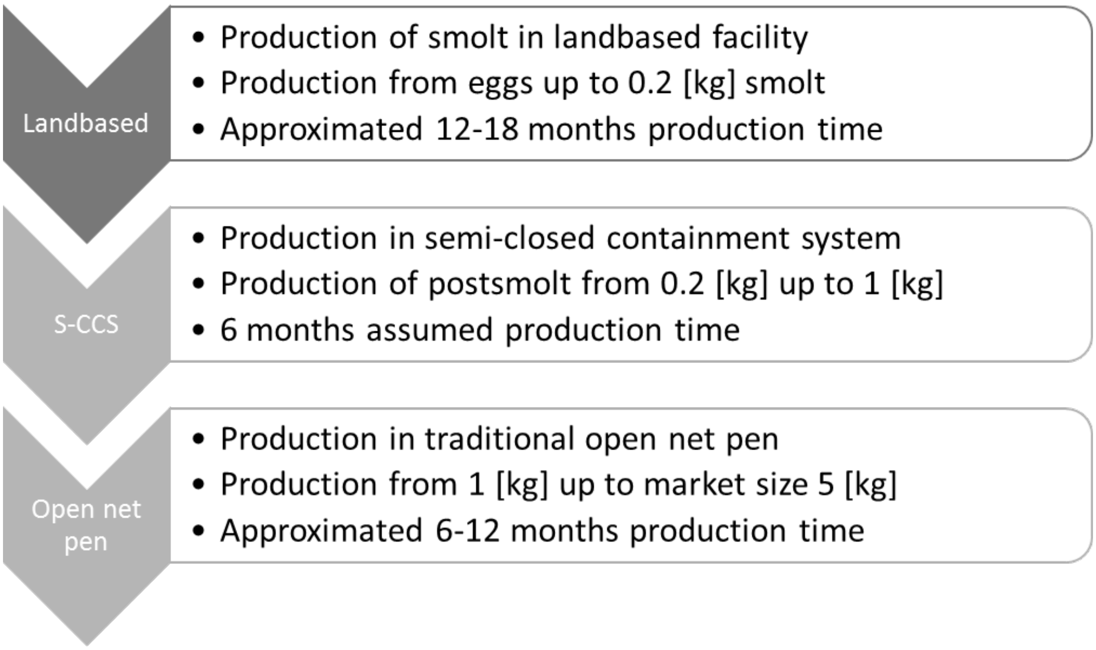
# Chapter 7

# Proposed strategies

The different strategies will be evaluated against each other and more or less seen in light of todays traditional production regime.

## 7.1 Strategy I: Postsmolt in S-CCS

Producing postsmolt in S-CCS has been proposed regularly in recent years (Lyngøy, 2012; Terjesen, 2014). Now that prototypes tested shows good results regarding growth, feed conversion ratio and high degree of survival (Handeland et al., 2015; F. Nilsen, 2017), many are interesting in implementing S-CCS in their production regime (Joensen, 2017).



**Landbased**

- Production of smolt in landbased facility
- Production from eggs up to 0.2 [kg] smolt
- Approximated 12-18 months production time

**S-CCS**

- Production in semi-closed containment system
- Production of postsmolt from 0.2 [kg] up to 1 [kg]
- 6 months assumed production time

**Open net pen**

- Production in traditional open net pen
- Production from 1 [kg] up to market size 5 [kg]
- Approximated 6-12 months production time

Figure 7.1: Schematic representation of the production strategy with comments to each stage. A similar strategy has been presented by Terjesen (2014) earlier and is the application of S-CCS where it is done most research.

Table 7.1: Assumed strengths and weaknesses of introducing S-CCS in postsmolt stage

| **Strengths** | **Weaknesses** |
|---|---|
| Reduced time exposed in sea | Economic investment |
| High degree of survival in S-CCS | Volume and capacity |
| Better transition to the sea with large smolt | Need for water treatment |
| Reduced mortality in the sea phase | Energy demand |
| Potential for higher growth rate in S-CCS | Area conflict |
| More efficient use of sea sites | |

Table 7.2: Neptun system displayed with different densities applied for postsmolt production.

| **System** | **Volume [$m^3$]** | **Capacity [kg]** | **Density [$kg/m^3$]** | **Size [kg]** | **Amount [-]** | **Open net pens distributed to** |
|---|---|---|---|---|---|---|
| **Neptun** | 21000 | 1 575 000 | 75 | 1 | 1 575 000 | 8 |
| | 21000 | 1 050 000 | 50 | 1 | 1 050 000 | 5 |
| | 21000 | 525 000 | 25 | 1 | 525 000 | 3 |
| **200 000 limit** | 21000 | 200 000 | 10 | 1 | 200 000 | 1 |

This strategy involves applying the S-CCS to extend the production time in protected rearing environment, and reduce the time salmon are exposed in sea. Postsmolt up to one kilogram will be reared in protected environment, reducing the risk of sealice. This can reduce the cost of delousing and operations related to sealice. Neptun are used in calculations and to illustrate the relation to open net pens. It is important that dimensions and capacity are adapted to the existing limits and regulations set. A production volume of 21 000 [$m^3$] with 200 000 postsmolt of one kilogram, will have a density of around 10 [$kg/m^3$]. A low density, as research from Calabrese et al. (2017) suggest.

In table 7.2 Neptun is used to show production capacity related to density and traditional open net pens. It is unknown what density Neptun is designed for, but if 75 [$kg/m^3$] is used it results in huge amount of individuals in the system which can be seen as a risk. Because of the large volume and the cost of operating such a system it is most likely that it is designed for more than 200 000 individuals, but how many is still unknown. Applying a density of 75 [$kg/m^3$] gives Neptun a possibility to distribute from one unit out to approximately eight traditional open net pens. This means one Neptun unit can supply one site with eight open net pens with postsmolt at one kilogram.

Table 7.3: Number of Neptun units required to produce all smolt in Norway up to one kilogram.

| **Capacity [kg/year/unit]** | **Weight difference [kg]** | **Units [-]** |
|---|---|---|
| 3 150 000 | 250 000 000 | 80 |

Table 7.4: Increased smolt size, means increased biomass produced in S-CCS before transfer to open sea production units. This difference is calculated to be 250 [million kg], which then again can be used to estimate how many units are required to produce all smolt in Norway up to one kilogram in a system like Neptun. Assuming average smolt size today to be 200 gram.

| | **Amount [kg]** | **Smolt size [kg]** |
|---|---:|---:|
| | 62 000 000 | 0.2 |
| | 312 000 000 | 1 |
| Difference | 250 000 000 | 0.8 |

In 2015 it was produced approximately 312 million smolt. In table 7.4 the difference between producing 200 gram and one kilogram smolt is presented. One Neptun unit can produce 1.5 million postsmolt at one kilogram each cycle. One cycle is assumed to take approximately 6 months in optimal production environment. One unit can then produce 3 [million one kg] postsmolt in one year. To be able to produce all of todays 200 gram smolt up to one kilogram will then require 80 Neptun units as displayed in table 7.3.

With higher densities the need to add oxygen are crucial. If oxygen is not added there will be a need for increasing the water flow into the system. This will result in high pumping power, more technical equipment and cost. The risk and consequences increase. If an event, like getting a disease would happen this will have a huge negatively impact on the production consisting of 1.5 million individuals.

### 7.1.1 Time in sea

This strategy could potentially reduce the time in sea with approximately 30-50% compared to todays traditional production. If we assume that the time in sea is linear with the amount of operations needed we estimate cost of operations and handling to reduce in the same range. Resulting in a 40-50% decrease in other expenses in the production cost detail. This criterion will then reduce one of the challenges of increasing production costs. S-CCS in tests has shown little or no problems related to sealice (Terjesen, 2017; Handeland et al., 2015).

### 7.1.2 Mortality

Research suggest that it is possible to achieve mortality in S-CCS at low as 1%. Tests from Neptun showed a 0.4% mortality (Handeland, 2016), meaning it is possible to achieve a great survival rate when producing in S-CCS. If assumed that mortality is approximately 3% in traditional open net pen production up to one kilogram, we can estimate mortality to potentially be reduced by 2%. The assumption is that total mortality is 20% throughout the cycle in sea and that mortality is equal distributed throughout the time in sea.

### 7.1.3 Cost

Cost of producing a S-CCS unit, like Neptun is assumed to be between 40-60 [million NOK], but this is of course affected by the amount of units produced and the technical specifications. These estimates are quite uncertain because of the lack of data. Iversen et al. (2013) estimated the investment to be 2 500 [NOK/$m^3$] for S-CCS , which would price Neptun at 52.5 [million NOK]. If this strategy is suppose to produce all the smolt in Norway from 0.2 to one kilogram there will be need of approximately 80 Neptun units. This gives a total investment cost of 4-5 [billion NOK], not taking into account cost of site surveys and other additional costs related to establishment of possible new sites.

### 7.1.4 Efficiency

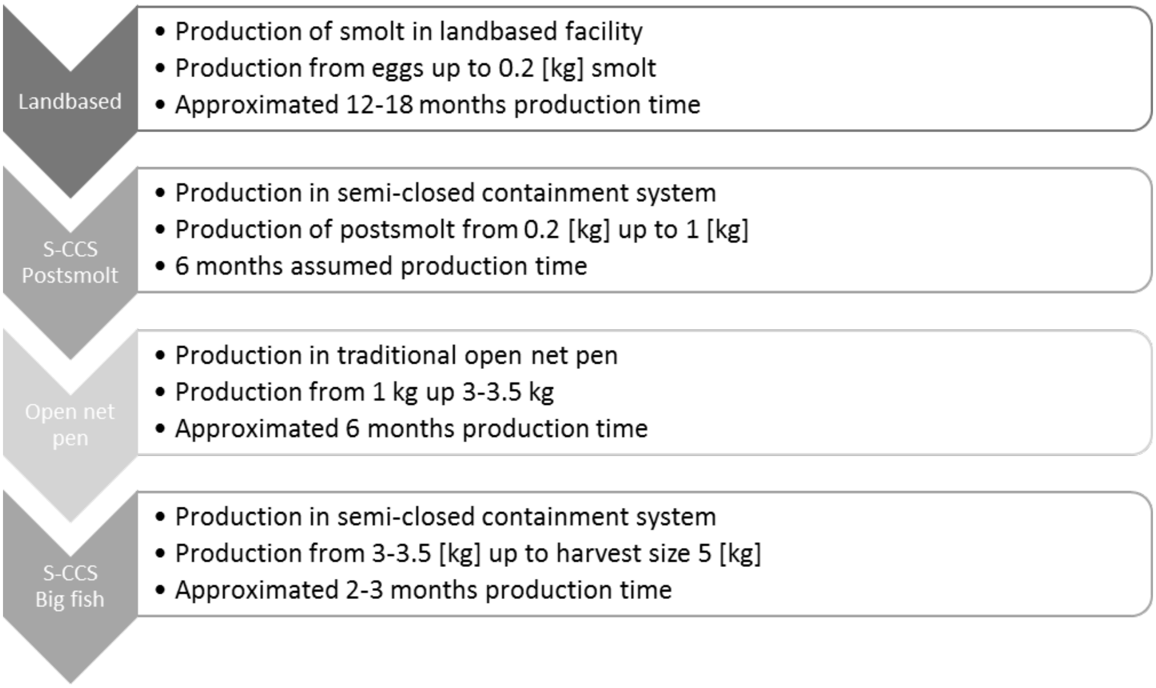
This strategy will make it possible to transfer postsmolt to open net pens at different times throughout the year and it could be possible to produce closer to the maximum allowed biomass limit at each site (Iversen et al., 2013). It might also influence which sites to use during the year and cause producers to apply the best sites at the given time, which is already being a strategy for some. Applying this strategy could make it possible to produce 1.5 to 2 cycles compared to todays production cycle in sea. It is possible to increase efficiency in this way, but it is uncertain if this could increase the volume due to the MAB limit.

### 7.1.5 Sites and area

Since most of the S-CCS today are designed for sheltered and protected areas it is most likely that sites closer to communities and housing must be utilized which could cause a more intensified conflict about sites and area. The amount of sites will increase and the need to occupy area will most likely increase when producing postsmolt in S-CCS.

## 7.2 Strategy II: Postsmolt + big fish

If S-CCS indicates good performance for postsmolt production, why should it be restricted to produce only postsmolt? There might be arguments to avoid other stages of the production cycle in open net pens. In this strategy the two first steps are identical as the postsmolt strategy, but in the last stage of production the Atlantic salmon are put back into S-CCS to reduce the time exposed in open sea even more. This might also reduce the risk of having to conduct operations, like delousing on big fish, close to market size. Loss in production when salmon are close to market size is costly and the consequences of high mortality have a huge impact economically.



- Production of smolt in landbased facility
- Production from eggs up to 0.2 [kg] smolt
- Approximated 12-18 months production time

- Production in semi-closed containment system
- Production of postsmolt from 0.2 [kg] up to 1 [kg]
- 6 months assumed production time

- Production in traditional open net pen
- Production from 1 kg up 3-3.5 kg
- Approximated 6 months production time

- Production in semi-closed containment system
- Production from 3-3.5 [kg] up to harvest size 5 [kg]
- Approximated 2-3 months production time

Figure 7.2: Schematic representation of the production strategy with comments to each stage.

Table 7.5: Assumed strengths and weaknesses of introducing S-CCS in postsmolt stage and close to market size.

| **Strengths** | **Weaknesses** |
|---|---|
| Considerably reduced time in open sea | Large investment |
| High degree of survival in S-CCS for postsmolt | Volume and capacity |
| Better transition to the sea with large smolt | Need for water treatment |
| Potential higher growth in S-CCS for postsmolt | Energy demand |
| More efficient use of sea sites | Intensified area conflict |
| | Research on big fish in S-CCS |

### 7.2.1 Time in sea

Including the last grow out period in S-CCS reduces the time exposed in open sea even further, in total between 50-60%. The reduction in this criteria is not that considerable compared to strategy one, but compared to traditional open net pens production it is significant. Operations and handling of bigger fish can potentially have a huge impact on production cost (J. Pettersen, 2017), due to the increased loss in production. Reducing the amount of operations even more could address this problem.

### 7.2.2 Mortality

One of the negative trends observed the last couple of years are that bigger salmon dies, which is an huge economically challenge (J. Pettersen, 2017). This means the producers already spent money growing the fish and loose income at the same time as production cost increases. Often mortality of big fish are related to disease or handling related to delousing. By producing the salmon in S-CCS in the last stage of their life cycle there could be a potential to reduce the mortality on big fish and by that reduce the average weight on dead-fish. This is not documented and are mainly assumptions to conduct the analysis.

### 7.2.3 Cost

Compared to strategy I this strategy will increase the investment cost to be approximately 9-10 [billion NOK]. To be able to produce all the postsmolt in Neptun it will be a need of approximately 80 units. Assuming one Neptun unit is capable of producing four cycles each year gives a total capacity of 1 260 000 [kg/unit/year]. We then need to take a look at how many units are needed to be able to produce all of the Norwegian salmon production during one year, from three to five kilogram.

Even though the turnover are higher than for postsmolt, 2-3 months, in production units for Atlantic salmon close to market size, the amount of units required are the same as for postsmolt production. This is because of the fish density and the fact that the number of fish in each unit is 1/5 compared to postsmolt at one kilogram. Each unit are able to produce four generations each year, from three to five kilogram. Resulting in a demand of approximately 80 units.

Table 7.6: Neptun system shown with different densities applied for close to market size production for one production cycle. During one year, one Neptun unit can produce four cycles of big fish, meaning the capacity reach 315 000 * 4 = 1 260 000 [kg/unit/year].

| System | Volume [$m^3$] | Capacity [kg/cycle] | Density [kg/$m^3$] | Size [kg] | Amount [-] | Open net pens distributed from |
|---|---|---|---|---|---|---|
| **Neptun** | 21000 | 1575000 | 75 | 5 | 315000 | 2 |
| | 21000 | 1050000 | 50 | 5 | 210000 | 1 |
| | 21000 | 525000 | 25 | 5 | 105000 | 1 |
| **200k limit** | 21000 | 1000000 | 48 | 5 | 200000 | 1 |

Table 7.7: Biomass produced from three to five kilogram during one year of production. This provides the basis for how many units that are needed to produce the same amount in S-CCS. Weight needed produced are based on the number of smolt put to sea in 2015 and the difference in weight from three to five kilogram.

| Capacity [kg/year/unit] | Weight needed produced [kg/year] | Units [-] |
|---|---|---|
| 6 300 000 | 500 000 000 | 80 |

### 7.2.4 Efficiency

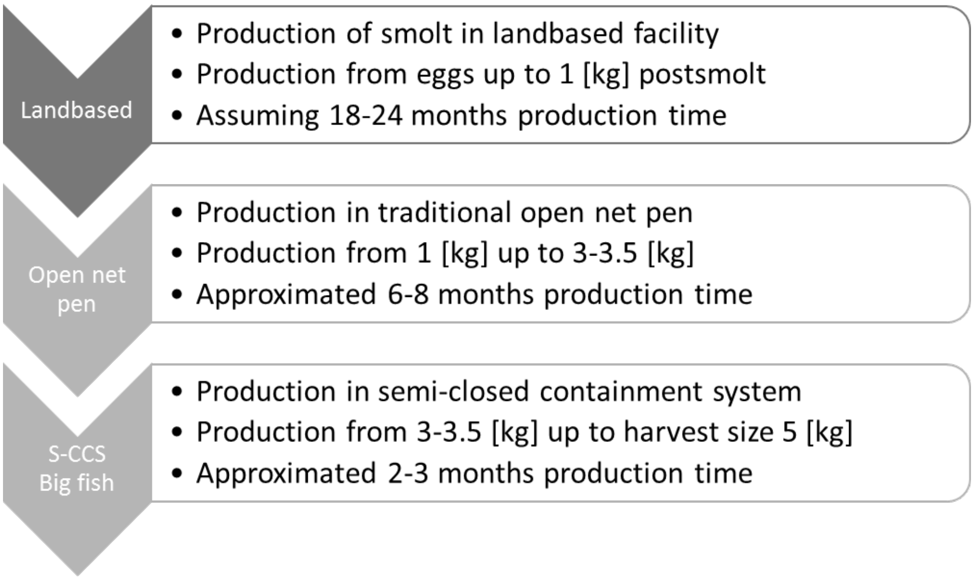
This strategy means that traditional open net pens will be used for even a shorter period of time for each cycle, and that it is possible to utilize the best sites more efficiently by fallowing when site specifications are not optimal, e.g increase of sea lice, diseases, algae bloom and exposed to storm season. Each site can potentially produce 2-3 cycles compared to todays production of one cycle in sea.

### 7.2.5 Sites and area

Producing postsmolt and Atlantic salmon close to market size in S-CCS will require more sites and production units. It then follows that there will be a more intensified area conflict inshore. The amount of sites and area will increase more compared to strategy I.

## 7.3 Strategy III: Postsmolt on land and big fish in S-CCS

Strategy III involves a prolonged production on land before the sea phase ending with production in S-CCS for the last grow-out stage. Extending the production on land could potentially have many benefits, like reduced mortality and faster growth rates. On the other hand would a prolonged production on land demand huge investments in the existing smoltproduction infrastructure. Mathisen (2016) points out that if all postsmolt in Norway are to be produced up to one kilogram on land it will require investments in the range of 40-50 [billion NOK] using RAS. Investments in this range can seem unrealistic, but it does not change the fact that increasing the production time on land could have other benefits.



- Production of smolt in landbased facility
- Production from eggs up to 1 [kg] postsmolt
- Assuming 18-24 months production time

- Production in traditional open net pen
- Production from 1 [kg] up to 3-3.5 [kg]
- Approximated 6-8 months production time

- Production in semi-closed containment system
- Production from 3-3.5 [kg] up to harvest size 5 [kg]
- Approximated 2-3 months production time

Figure 7.3: Schematic representation of the production strategy with comments to each stage.

Table 7.8: Assumed strengths and weaknesses of introducing S-CCS in postsmolt stage and close to market size

| Strengths | Weaknesses |
|---|---|
| Reduced time in open sea | Huge economic investment |
| High degree of survival landbased | Volume and capacity |
| Potential faster growth in S-CCS | Need for water treatment |
| More efficient use of sea sites | Energy demand |
| Reduced costly operations in sea | Area conflict |
| | Research on big fish in S-CCS |

As seen in figure 7.3 the production time in open net pens will be reduced equivalent as for strategy two. In table 7.8 the strengths and weaknesses in this strategy are listed.

### 7.3.1 Time in sea

Producing for a longer period on land and including the S-CCS in the last grow-out phase reduces the time exposed in open sea with approximately 50-60%, as for strategy II. Resulting in a reduction in the other operation expenses in production cost, due to the decrease in number of operations and handling. Production cost for a prolonged production on land are not taken into account.

### 7.3.2 Mortality

Postsmolt production in RAS systems on land are already established as a stable and effective production method. Prolonging the time in these systems can, compared to producing in open net pens, reduce the mortality because of the increased degree of control in production environment. It is difficult to estimate if this way of producing postsmolt is better compared to producing in S-CCS floating in sea. It is assumed that mortality is lower compared to todays production regime. Potentially reducing the need for operations and handling will reduce the mortality of fish close to market size, as they are reared in S-CCS floating in sea.

### 7.3.3 Cost

The demand for number of production units are approximately the same as for the postsmolt strategy I. This gives a investment cost for S-CCS in the range of 4-5 [billion NOK]. When it comes to producing postsmolt on land up to one kilogram this will require a huge investment as mentioned earlier. Mathisen (2016) estimated the cost of increasing the size of smolt produced on land to be 4-5 [billion NOK/100 gr increase]. This will require a total of 40-50 [billion NOK] in investments, making this alternative extremely costly.

### 7.3.4 Efficiency

Increasing smolt size and reducing the production time in open net pens, could potentially increase the efficiency of sites in sea. It is possible to utilize different sites at different times and constantly produce closer up to maximum allowed biomass. Efficiency for this strategy will be as for strategy II, 2-3 production cycles compared to todays one production cycle in sea.

### 7.3.5 Sites and area

S-CCS will increase the number of production units, resulting in more sites needed and a more intensified area conflict as described for the other strategies. The special feature of strategy III is that it will demand more space on land for postsmolt production in landbased facilities.

# Chapter 8

# Analysis and results

Applying the ROC and AHP methods results in suggested solutions and asses what strategy that are most suitable based on the criteria.

## 8.1 ROC results

The ROC method is described in section 2.2.1 and as mentioned the order of ranking is essential for converting ranking to weights. Ranked criteria is shown in table 8.1. Figure 8.1 displays the values in table 8.1 graphically.

Table 8.1: Ranking converted to weights using equation 2.1.

| Criteria | Ranking | Weight |
|---|---:|---:|
| Time in sea | 1 | 0.457 |
| Mortality | 2 | 0.257 |
| Cost | 3 | 0.157 |
| Efficiency | 4 | 0.090 |
| Area and sites | 5 | 0.040 |

### 8.1.1 Value functions

Now it is time to give each strategy score on each criteria, to be able to asses which strategy is the best. Scores are in this case between zero and one, where zero is worst score and one is best. The scores, as individual value functions, are normalized. Each value function is presented as either a linear or exponential function in this study.

Time in sea is chosen as an exponential function where lower limit is 24 months and the upper limit is 4 months. This means the time in sea must be reduced significantly compared to the traditional production before it will give a beneficial higher score. See figure 8.2a.

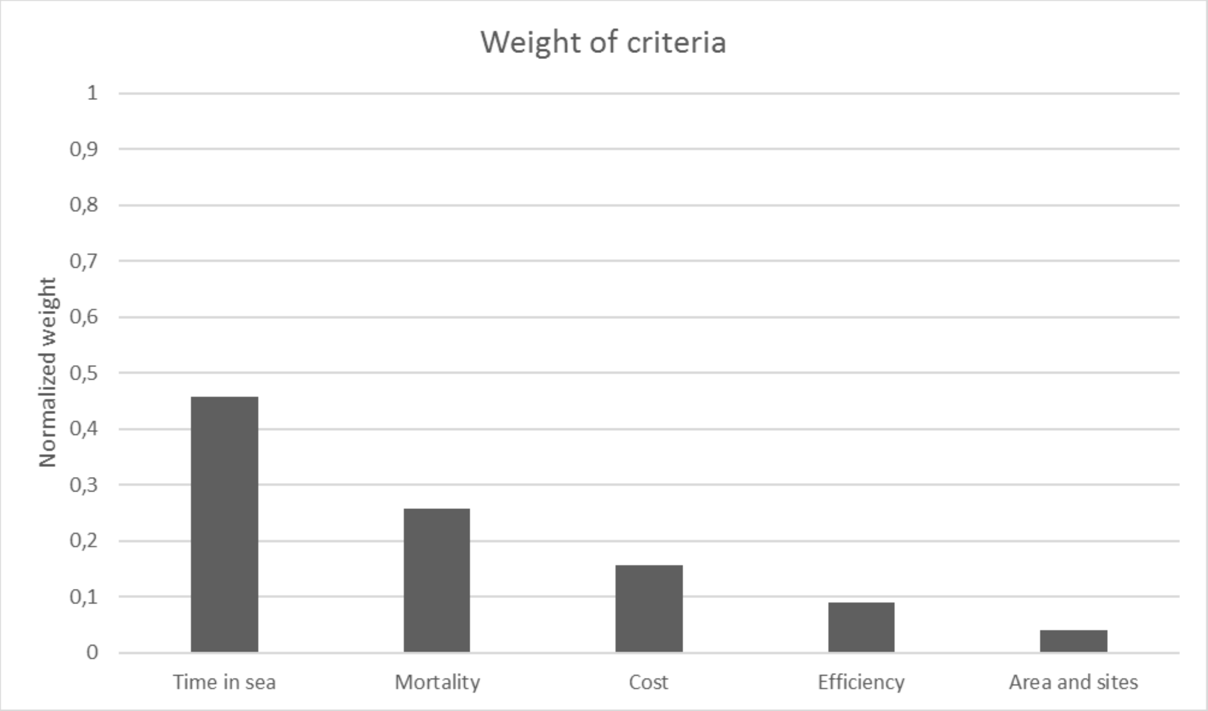
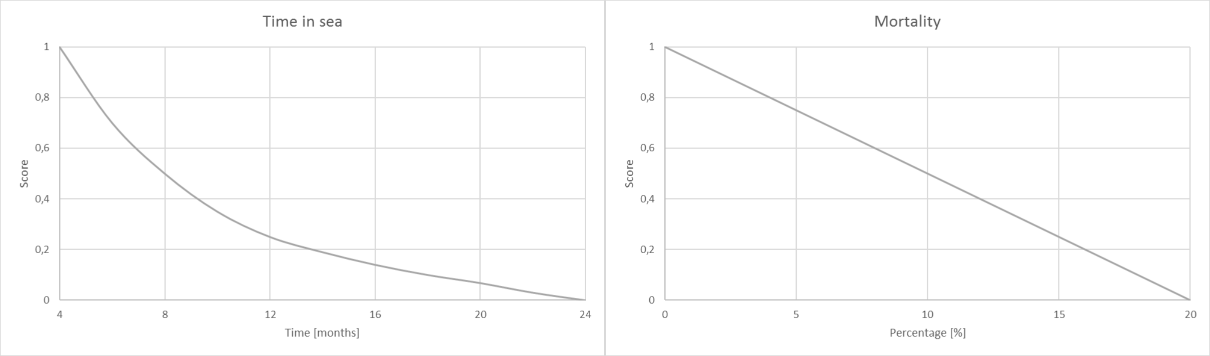


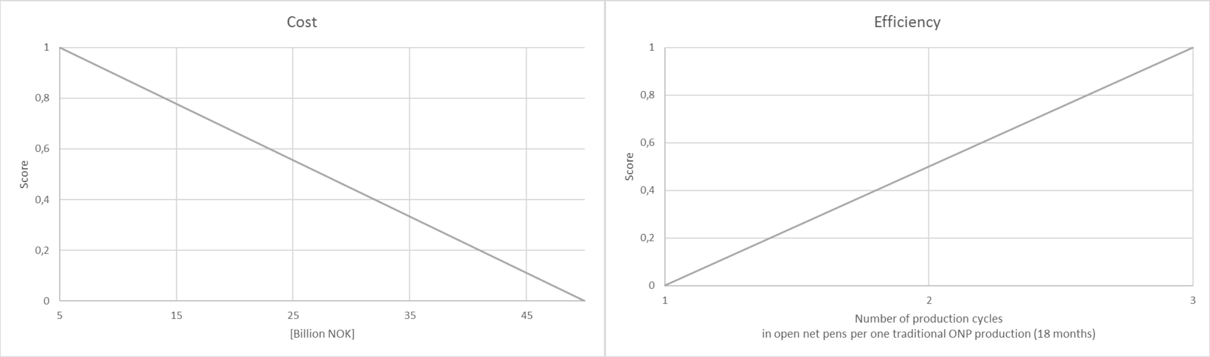
Figure 8.1: Graphical representation of weights.

Also seen in figure 8.2, is the mortality value function, 8.2b. This is set as a linear function were score is linearly related to the percentage decrease in mortality expected. Upper limit for the mortality is set as todays approximated actual mortality, 20%. To achieve a zero mortality rate is quite extreme so all efforts on reducing mortality will result in a linearly higher score.

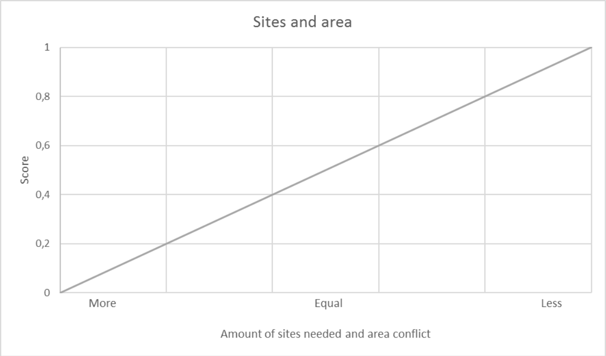
The cost value function is set as an linear function where number of units and cost is linearly related. Upper limit is put to 50 [billion NOK] and the lower limit is at 5 [billion NOK], as seen in figure 8.2c. Efficiency as well as sites and area are chosen to be linear functions. Efficiency is describes as the number of production cycle each sea site can produce, compared to traditional open net pen production of 18 months, as seen in figure 8.2d. Sites and area are given score based on the need for sites and the possibly intensified area conflict, where more sites have a negatively effect on the score.



(a) Time in sea (b) Mortality



(c) Cost (d) Efficiency



(e) Sites and area

Figure 8.2: Individual value functions for the five criteria.

### 8.1.2 ROC weights and score

In table 8.2 the strategies are given scores based on the arguments presented in chapter 7 and value functions presented. Scores multiplied with weights then gives a value function for each strategy and a total score for the given alternative.

Table 8.2: Weights and score for the given criteria and strategies respectively.

| **Criteria** | **Ranking** | **Weight** | **I** | **II** | **III** |
|---|---|---|---|---|---|
| Time in sea | 1 | 0.457 | 0.7 | 0.8 | 0.8 |
| Mortality | 2 | 0.257 | 0.6 | 0.6 | 0.8 |
| Cost | 3 | 0.157 | 1.0 | 0.6 | 0.1 |
| Efficiency | 4 | 0.090 | 0.6 | 0.9 | 0.9 |
| Area and sites | 5 | 0.040 | 0.4 | 0.2 | 0.2 |
| Total | | 1.000 | 0.700 | 0.702 | 0.675 |

The score for each of the strategies are then calculated. Equation 8.1 show the calculation for strategy I as an example.

$$(0.457 * 0.7) + (0.257 * 0.6) + (0.157 * 1.0) + (0.090 * 0.6) + (0.040 * 0.4) = 0.700 \tag{8.1}$$

Figure 8.3 is a graphical representation of the results from the ROC analysis showing the different score for each criteria for every strategy. Strategy I and II score almost identical using the ROC method while strategy number III scores somewhat below, struggling especially with the cost criteria.

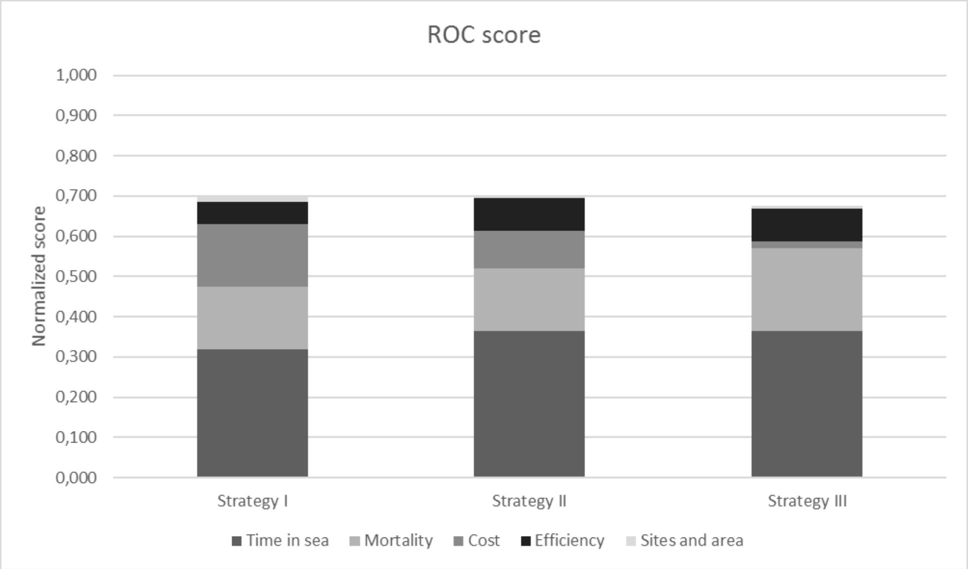


Figure 8.3: Total score from the ROC analysis.

## 8.2 Analytic hierarchy process

Compared to the ROC method, the AHP use pairwise comparison when doing the evaluation of criteria and strategies. First the comparison matrix for the criteria is completed, as shown in table 8.3.

### 8.2.1 Comparison matrix for criteria

It is clear by looking at the comparison matrix that time in sea is the dominant criterion. It is strong or essential compared to both mortality and cost which is the following. Time in sea is also extremely more important than sites and area. Mortality is equally important to cost, but is essential more important than efficiency and extremly more important than sites and area. The normalized comparison matrix is shown in table 8.4.

We then control the consistency for these comparisons to confirm that they are not totally random. To see consistency control for all the comparison matrices, please see appendix B. For the normalized comparison matrix all the rows are summarized and average is calculated before the MMULT-function is used to calculate consistency measure. The CI are then calculated applying equation 2.9, before CR are found by dividing CI on RI.

Table 8.3: Comparison matrix for the five criteria.

| | **Time in sea** | **Mortality** | **Cost** | **Efficiency** | **Sites and area** |
|---|---|---|---|---|---|
| Time in sea | 1 | 5 | 5 | 7 | 9 |
| Mortality | 1/5 | 1 | 1 | 5 | 9 |
| Cost | 1/5 | 1 | 1 | 5 | 9 |
| Efficiency | 1/7 | 1/5 | 1/5 | 1 | 3 |
| Sites and area | 1/9 | 1/9 | 1/9 | 1/3 | 1 |

Table 8.4: Normalized comparison matrix.

| | **Time in sea** | **Mortality** | **Cost** | **Efficiency** | **Sites and area** |
|---|---|---|---|---|---|
| Time in sea | 0.60 | 0.68 | 0.68 | 0.38 | 0.29 |
| Mortality | 0.12 | 0.14 | 0.14 | 0.27 | 0.29 |
| Cost | 0.12 | 0.14 | 0.14 | 0.27 | 0.29 |
| Efficiency | 0.09 | 0.03 | 0.03 | 0.05 | 0.10 |
| Sites and area | 0.07 | 0.02 | 0.02 | 0.02 | 0.03 |
| Total | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

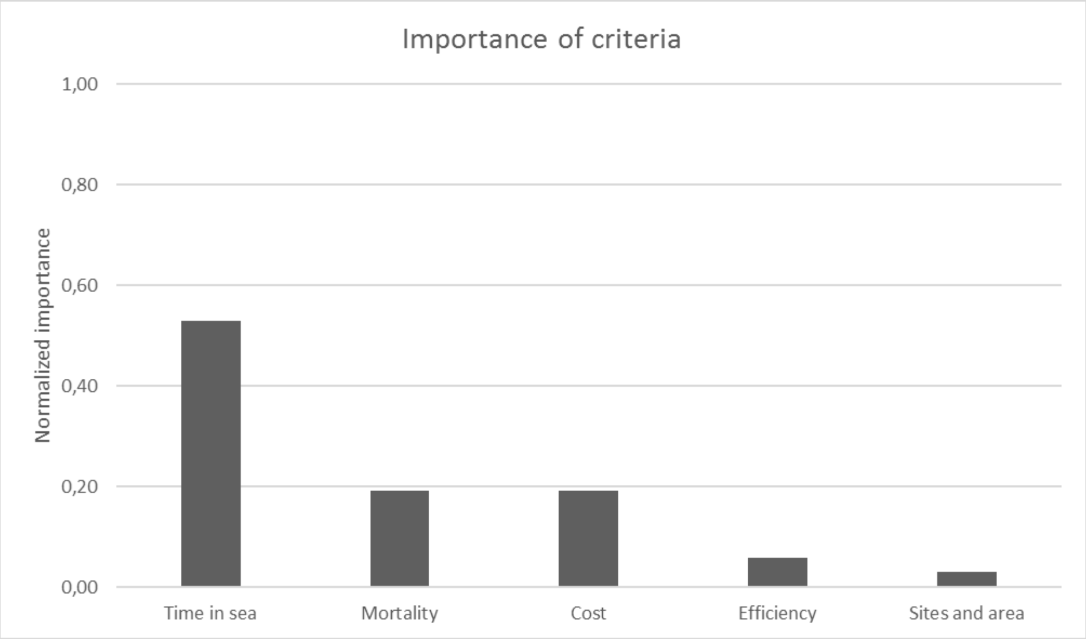


Figure 8.4: Graph representing the importance of the five criteria. Values are represented in table 8.5 as average.

Table 8.5: Consistency measure for comparison matrix for criteria.

| **Total** | **Average** | **Consistency Measure** |
|---|---|---|
| 2.64 | 0.53 | 5.90 |
| 0.96 | 0.19 | 5.47 |
| 0.96 | 0.19 | 5.47 |
| 0.29 | 0.06 | 5.12 |
| 0.15 | 0.03 | 5.08 |
| $\lambda_{max}$ | | 5.41 |

Table 8.6: Consistency check.

| Number of comparisons | 5,00 |
|---|---|
| Average consistency | 5,41 |
| CI | 0,10 |
| RI | 1,12 |
| Consistency ratio | 0,09 |
| Consistent? | Yes |

When the average consistency, as $\lambda_{max}$, is known it is possible to calculate the consistency index using equation 2.9, look up the random index and control that consistency ratio, CR, is <0.1. Seen in table 8.6, the consistency ratio is below 0.1, which means that by Saaty (1980), the comparisons are consistent and not totally random. Figure 8.4 displays the importance of criteria graphically after doing the pairwise comparison.

### 8.2.2 Comparison matrices for criteria

Strategies are now compared applying the same technique for every criteria. To see full calculation for the AHP-method see appendix B. The three different strategies are evaluated for each criteria, using the comparison matrix. Strategy II and III have the possibility to shorten the time in sea somewhat more than strategy I, resulting in a higher importance for strategy II and III.

Mortality is difficult to predict, but since research concerning mortality of postsmolt in S-CCS has come further than for big fish in closed containment systems, strategy I gets the highest level of importance compared to the others on this criteria. Strategy III, rearing postsmolt on land, is doing moderately better than strategy II because of increased research in this field and focus on possible low mortality in landbased production. Cost is simpler to estimate and strategy I, postsmolt in S-CCS, is extremely more cost efficient than than the landbased alternative, strategy III. Efficiency, as efficient use of sea sites, is a complex criteria and these comparisons are made based on how many production cycles that each strategy can produce in open net pens compared todays average of approximately 18 months. Strategy II and III score slightly better compared to strategy I.

Table 8.7: Strategies evaluated for time in sea.

| **Time in sea** | **Strategy I** | **Strategy II** | **Strategy III** |
|---|---|---|---|
| Strategy I | 1.0 | 1/2 | 1/2 |
| Strategy II | 2.0 | 1.0 | 1.0 |
| Strategy III | 2.0 | 1.0 | 1.0 |

Table 8.8: Strategies evaluated for mortality.

| **Mortality** | **Strategy I** | **Strategy II** | **Strategy III** |
|---|---|---|---|
| Strategy I | 1 | 5 | 3 |
| Strategy II | 1/5 | 1 | 1/3 |
| Strategy III | 1/3 | 3 | 1 |

Table 8.9: Strategies evaluated for cost.

| **Cost** | **Strategy I** | **Strategy II** | **Strategy III** |
|---|---|---|---|
| Strategy I | 1 | 3 | 9 |
| Strategy II | 1/3 | 1 | 7 |
| Strategy III | 1/9 | 1/7 | 1 |

Table 8.10: Strategies evaluated for efficiency.

| **Efficiency** | **Strategy I** | **Strategy II** | **Strategy III** |
|---|---|---|---|
| Strategy I | 1 | 1/2 | 1/2 |
| Strategy II | 2 | 1 | 1 |
| Strategy III | 2 | 1 | 1 |

Table 8.11: Strategies evaluated for sites and area

| **Sites and area** | **Strategy I** | **Strategy II** | **Strategy III** |
|---|---|---|---|
| Strategy I | 1 | 3 | 1/3 |
| Strategy II | 1/3 | 1 | 1/5 |
| Strategy III | 1 | 5 | 1 |

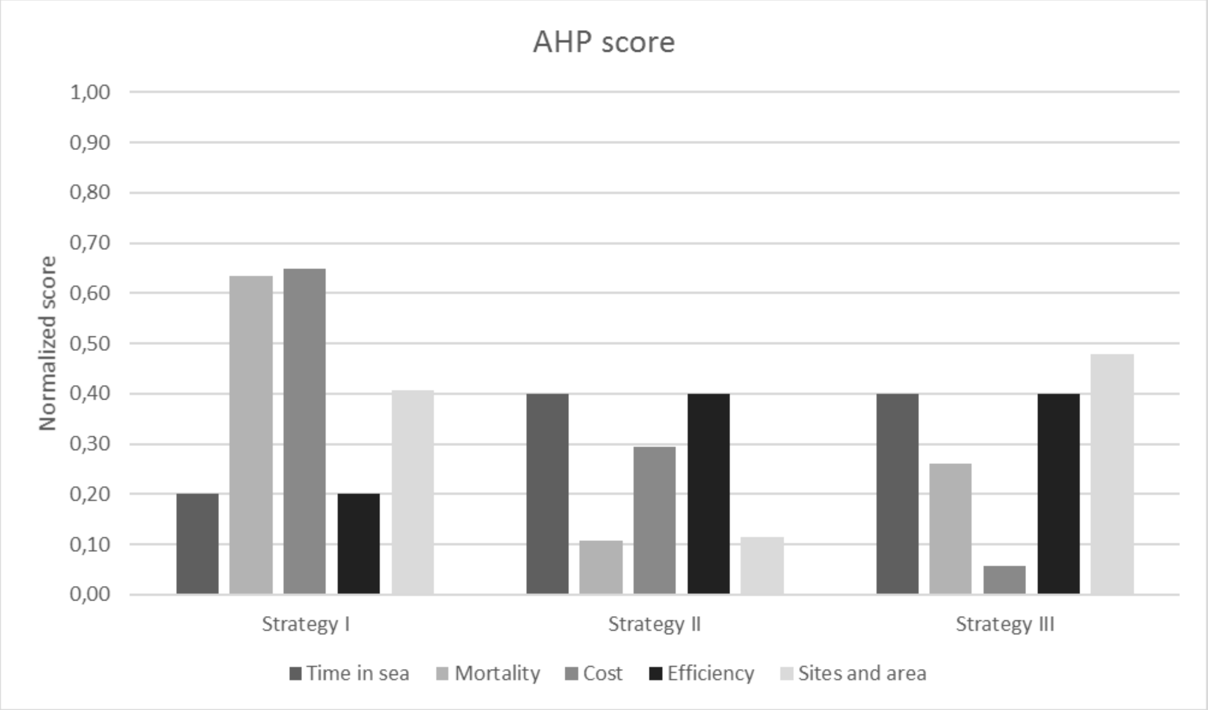


Figure 8.5: Normalized criteria score for each of the strategies.

Regarding the criteria demand for sites and area it is strategy I and III that score best. Strategy I compared to strategy II because it requires half the amount of sites, and strategy III because of the already ongoing development of landbased postsmolt, where already existing sites are being expanded. Figure 8.5 sums up the normalized criteria scores for each strategy.

Strategy I scores significantly better than the other alternatives on the criteria Mortality and Cost. Since these two criteria have a high level of importance in the analysis, it affect the results. Even though strategy II and III scores higher than strategy I on the criterion Time in sea, which is ranked as the most important criterion with importance of 0.53.

### 8.2.3 AHP result

When all the comparison matrices are created, normalized and controlled the final results can be calculated. Performing matrix-multiplication give results on which strategy that are preferred according to the criteria and comparison executed. The criteria preference matrix is basically the average for each strategy for every criteria, as seen in table 8.12. To give each strategy a score these values must be multiplied with the level of importance for each criteria, seen in table 8.13.

Table 8.12: Criteria preference matrix

| **Alternative** | **Time in sea** | **Mortality** | **Cost** | **Efficiency** | **Sites and area** |
|---|---|---|---|---|---|
| Strategy I | 0.20 | 0.63 | 0.65 | 0.20 | 0.41 |
| Strategy II | 0.40 | 0.11 | 0.29 | 0.40 | 0.11 |
| Strategy III | 0.40 | 0.26 | 0.06 | 0.40 | 0.48 |

Table 8.13: Average level of importance for each criteria.

| **Criteria** | Average level of importance |
|---|---|
| Time in sea | 0.53 |
| Mortality | 0.19 |
| Cost | 0.19 |
| Efficiency | 0.06 |
| Sites and area | 0.03 |

Table 8.14: Calculated score

| | **C#1** | **C#2** | **C#3** | **C#4** | **C#5** | **Score** |
|---|---|---|---|---|---|---|
| Strategy I | 0.106 | 0.121 | 0.124 | 0.012 | 0.012 | 0.375 |
| Strategy II | 0.212 | 0.020 | 0.056 | 0.023 | 0.003 | 0.315 |
| Strategy III | 0.212 | 0.050 | 0.011 | 0.023 | 0.014 | 0.310 |

Using the MMULT-function in Excel gives the results for each strategy. As shown in table 8.14 strategy I get the highest score out of the three alternatives. In figure 8.6 the total score for each strategy is shown, including the score for each criteria. Even though strategy II and III get a good score on the most important criterion Time in sea, they fall short in both mortality and cost criteria. Changes in the mortality comparison matrix can affect the result significantly.

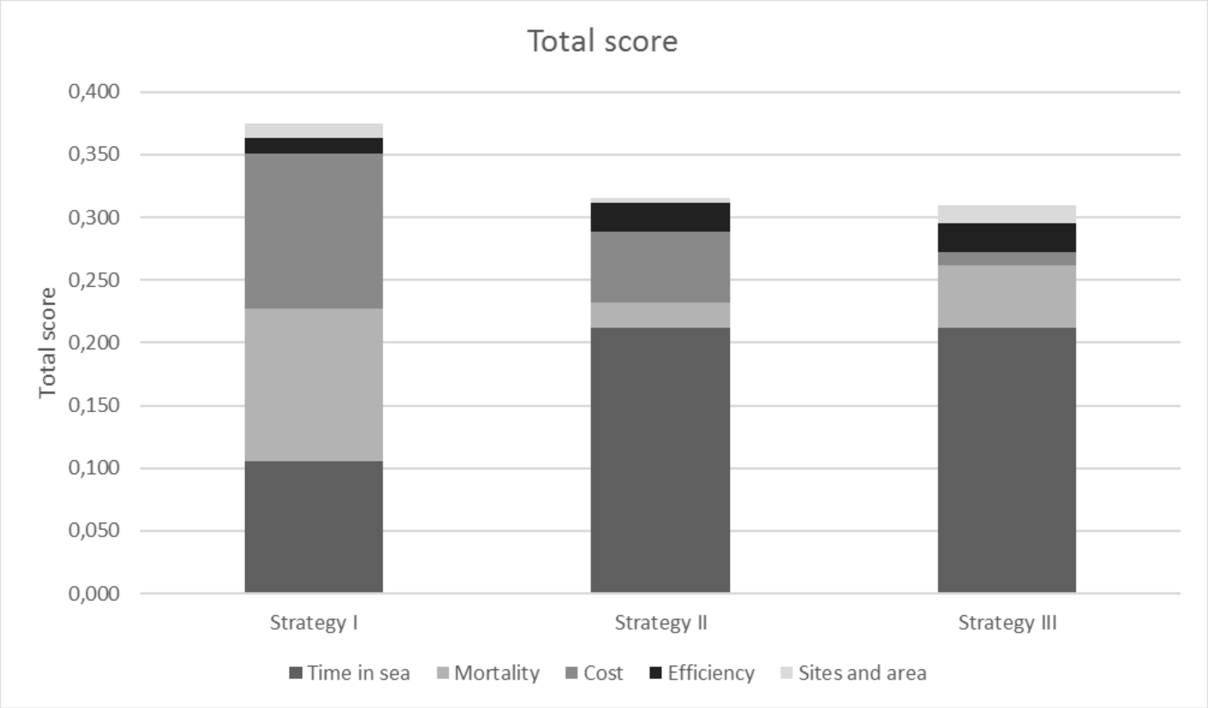


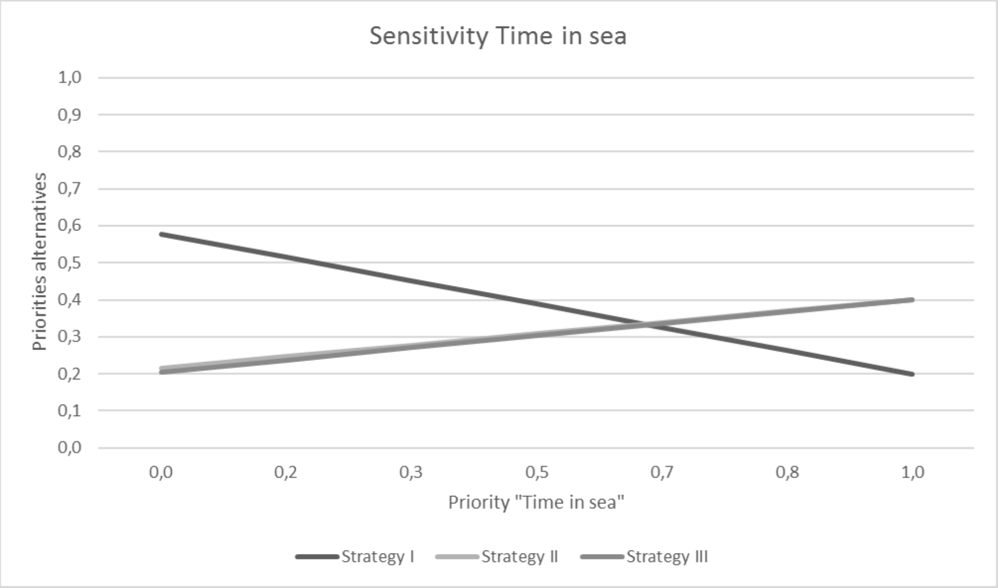
Figure 8.6: Total score for each strategy, representing the score on each criteria for all three strategies. Criteria are listed by importance, from *Time in sea* to *Sites and area.*

### 8.2.4 Sensitivity analysis

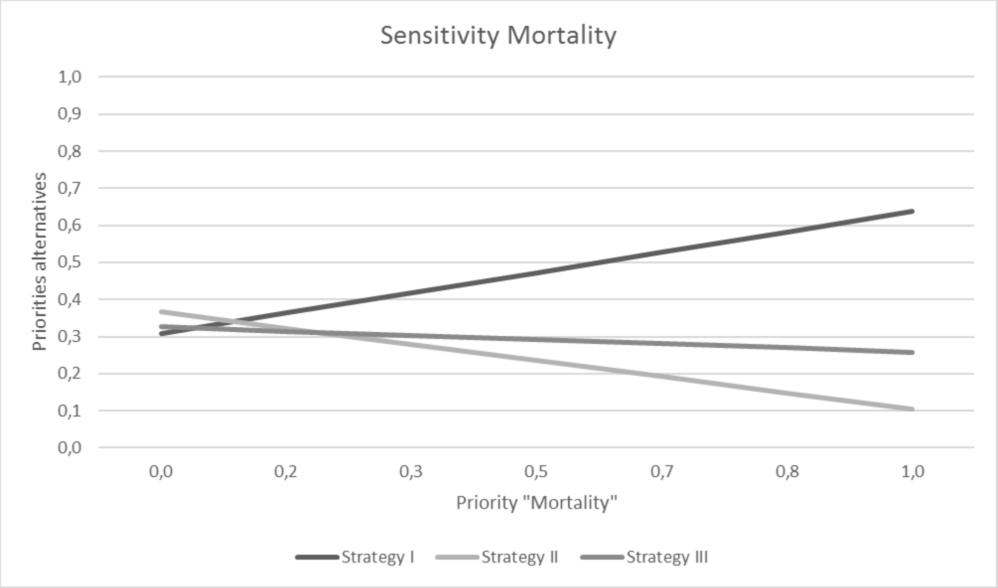
Sensitivity analysis is important to perform because it highlight the results in depth, by showing how changes in the criteria preferences affect the final results. Some will argue that the sensitivity analysis is even more interesting than the results themselves. Sensitivity analysis address the uncertainty of judgments. A sensitivity analysis also shows the robustness of the decisions made and highlight scenarios and possible other outcomes. It is recognized as a key element in developing models (Chen, Yu, & Khan, 2013). The free software, SuperDecisions v.2.8, was used to compute the sensitivity analysis before it was plotted using Excel.

Figure 8.7a illustrate that increasing the importance of Time in sea-criterion above 0.64 will change the result. Above 0.64 Strategy II will get the best total score. Strategy II and III are following each other across the priority range, but strategy III are never the preferred alternative. Sensitivity for the Mortality-criterion can also change the results, as priority lower than 0.097 will favor strategy II. Sensitivity analysis suggest that the Cost-criterion is quite similar to mortality, except the favored criterion if priority is low are strategy III.

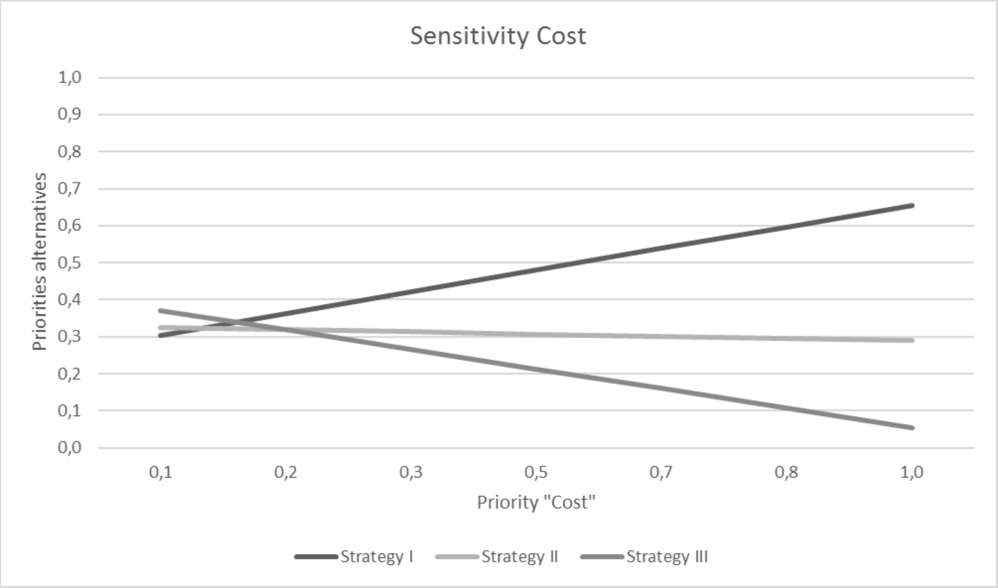
In figure 8.7d it is observed that strategy I are preferred as long as the priority of efficiency are beneath 0.24. Above this level, strategy II are favored, until Strategy II and III are equal from priority of 0.83. Sensitivity in Sites and area-criterion is favoring Strategy III at any level above 0.44.



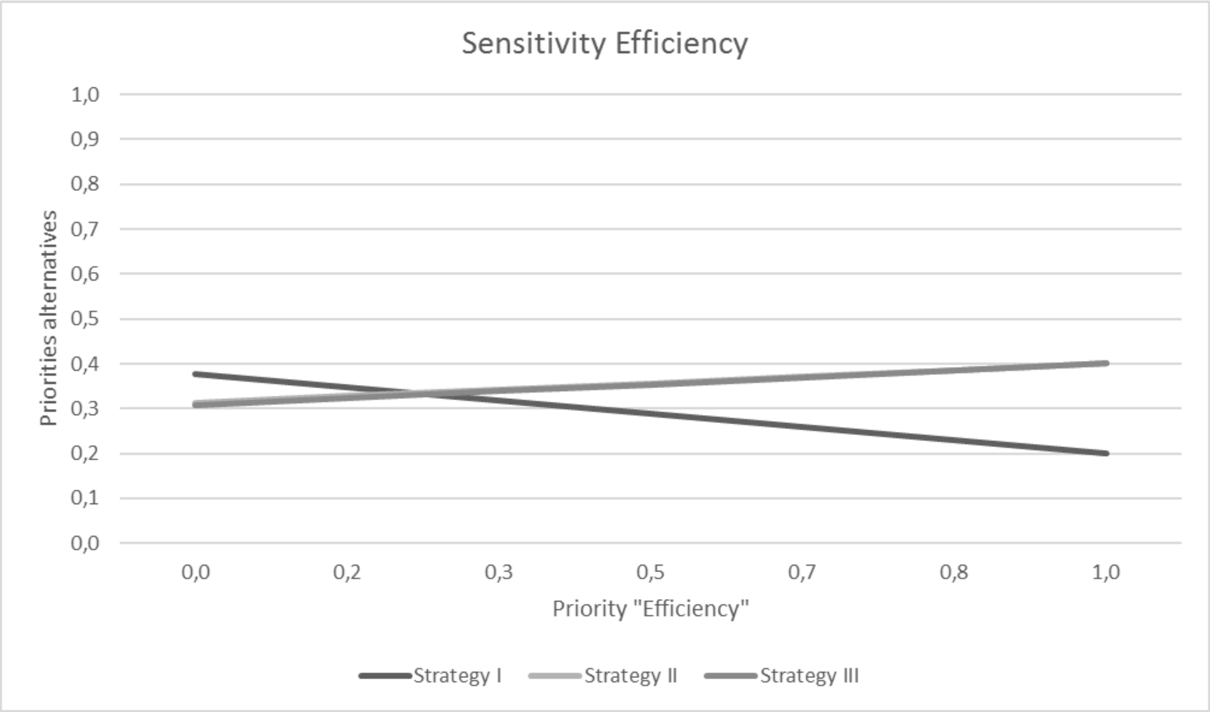
(a) Sensitivity Time in sea.



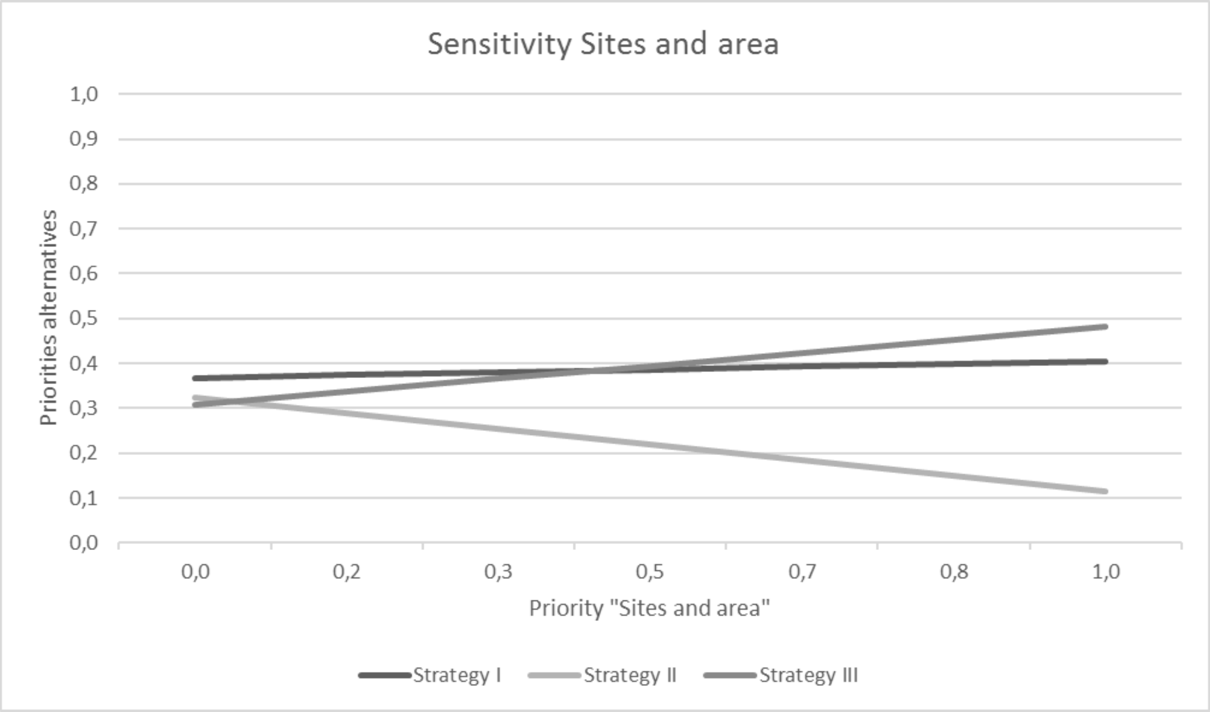
(b) Sensitivity Mortality.



(c) Sensitivity Cost.



(d) Sensitivity Efficiency.



(e) Sensitivity Sites and area.

## 8.3 Summary of comparison

Table 8.15: Comparing results from ROC and AHP.

| **Alternative** | **ROC** | **%** | **AHP** | **%** |
|---|---|---|---|---|
| Strategy I | 0,700 | 33,7 | 0,375 | 37,5 |
| Strategy II | 0,702 | 33,8 | 0,315 | 31,5 |
| Strategy III | 0,675 | 32,5 | 0,310 | 31,0 |

Applying the ROC method, with value functions, gave strategy II a small advantage over strategy I. Overall, there were little difference between the three alternatives. Applying the AHP and performing the pairwise comparisons gave different results than for the ROC. AHP analysis favored strategy I, while strategy II and III were a bit behind. In table 8.15 the results are stated. The AHP analysis had a greater difference in results as shown in table 8.15. Figure 8.8 displays the three different strategies in the ROC analysis and which criteria dominated their score.

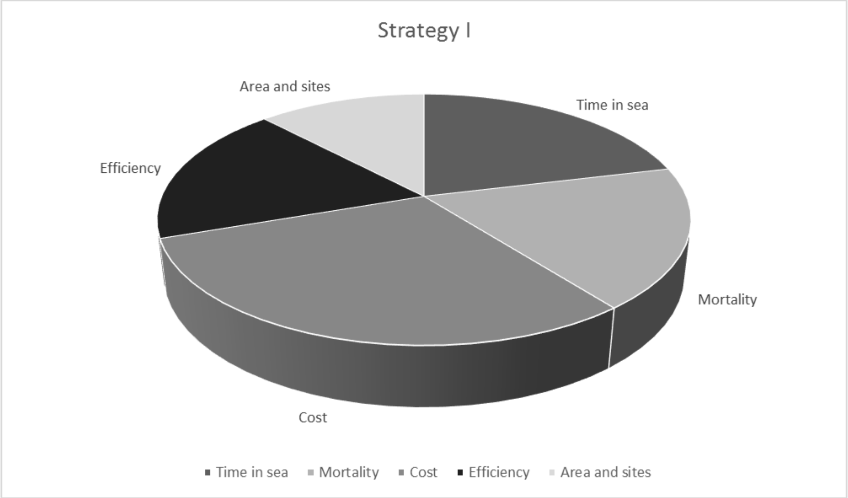
Figure 8.9 highlight what affected the total score for each strategy in the AHP analysis. Strategy II and III are highly dominated by the most important criteria, Time in sea. They score significantly less on the Mortality and Cost criteria, which is ranked as second and third most important. Due to this strategy I gets a higher total score. Strategy I score well on all the top three criteria. Figure 8.9 try to illustrate and display the differences between the strategies in the AHP analysis.

Table 8.16: Highlighted major differences in score. Mortality and cost are major contributors to strategy I dominance. Changes in the pairwise comparisons by the decision maker will change this drastically.

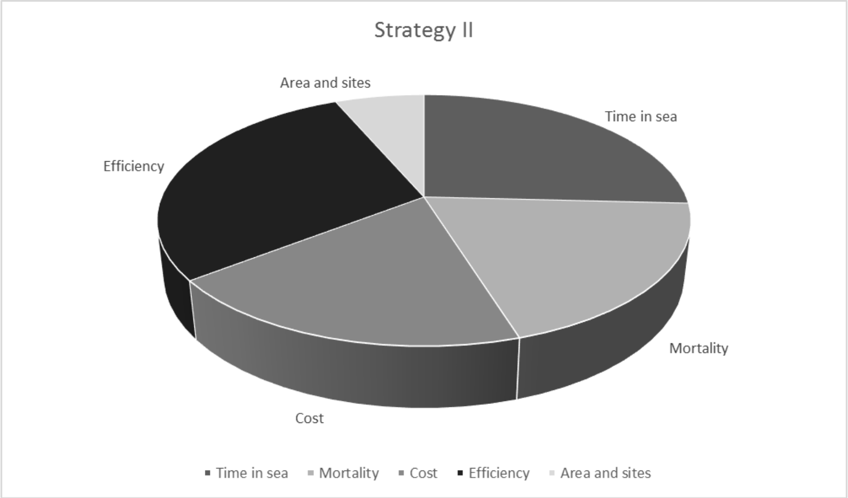
| **Alternative** | Time in sea | Mortality | Cost | Efficiency | Sites and area |
|---|---|---|---|---|---|
| Strategy I | 0,20 | 0,63 | 0,65 | 0,20 | 0,41 |
| Strategy II | 0,40 | 0,11 | 0,29 | 0,40 | 0,11 |
| Strategy III | 0,40 | 0,26 | 0,06 | 0,40 | 0,48 |

Table 8.17: Highlighted top three ranked criteria. These criteria affect the result the most as it stands.

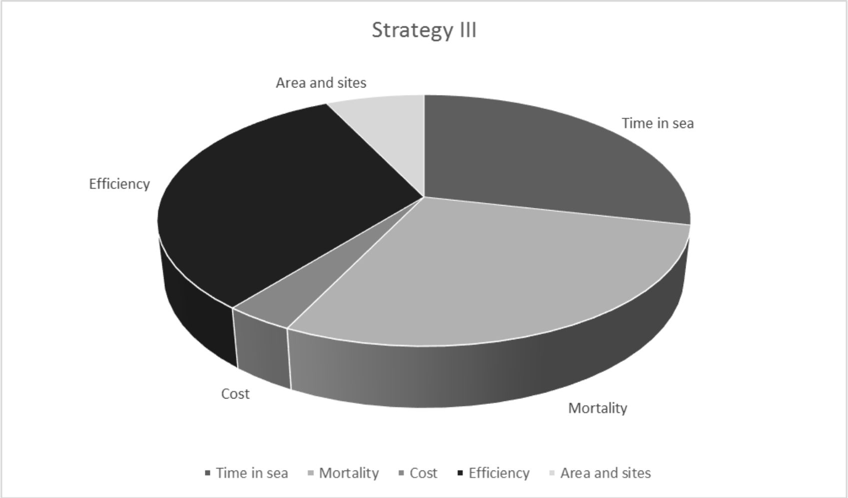
| **Criteria** | **Level of importance** |
|---|---|
| Time in sea | 0,53 |
| Mortality | 0,19 |
| Cost | 0,19 |
| Efficiency | 0,06 |
| Sites and area | 0,03 |



(a)

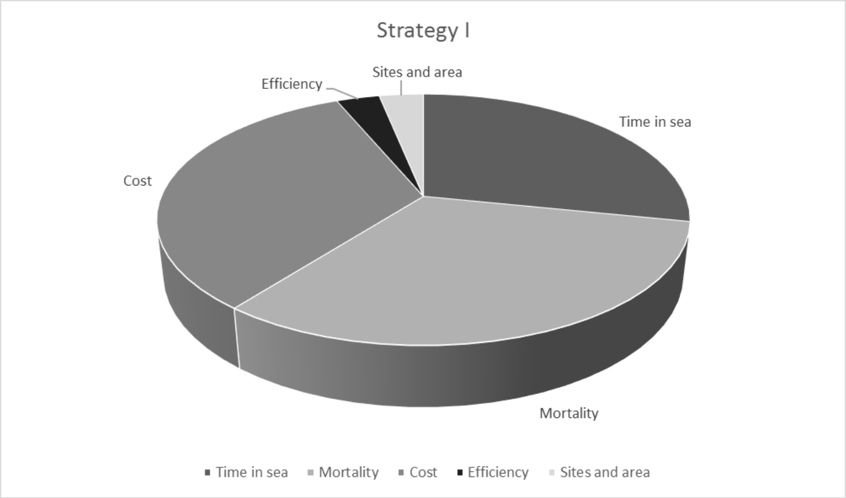


(b)



(c)

Figure 8.8: Diagram displaying the impact of each criterion in the ROC analysis. A small piece in the diagram indicates a low impact on the total score for the strategy. Strategy I total score is 0.700, strategy II total score is 0.702 and strategy III score a total of 0.675.



(a)

(b)

(c)

Figure 8.9: Diagram displaying the impact of each criterion in the AHP analysis. Time in sea criterion is dominating both strategy II and III, while strategy I have distributed domination between top three criteria. A small piece in the diagram indicates a low impact on the total score for the given strategy. Strategy III for instance, get a low score on cost. Strategy I total score is 0.375, strategy II total score is 0.315 and strategy III score a total of 0.310.

# Part IV

# Discussion and conclusion

# Chapter 9

# Discussion

## 9.1 Alternatives - proposed strategies

For the purpose of evaluating the three strategies the author has chosen five criteria deemed generally important for Atlantic salmon production in Norway at the time, and in someway directed towards S-CCS in sea. Different and more specific criteria could have been applied for the analysis, resulting in different solutions and recommendations. Criteria could also be ranked differently, and divided into sub-criteria, giving a different situation of the analysis. As research progress, more detailed information about criteria and quantified data could be applied in the analysis. The author is the decision-maker in this study and this must be emphasized.

Strategy I, producing postsmolt up to one kilogram in S-CCS in sea, is the one documented and backed up with most results and research. This effects the analysis since a more thoroughly documentation gives a robust basis arguing for the strategy and judgments executed. In the years to come this might change drastically as research is progressing.

Next to postsmolt production in S-CCS in sea, is the prolonged production of smolt on land in RAS facilities. This development is already ongoing as existing smolt facilities are expanding the production to be able to produce bigger smolt, postsmolt. Research and development concerning production of Atlantic salmon in RAS has come a long way and it shows good potential for postsmolt production. Strategy III, including this production stage, is in the analysis getting evenly good score, but the investment cost of increasing the total of Norway's smolt size with land based production is inhibiting the strategy to score best overall. Combined with this is the lack of research on Atlantic salmon close to market size in S-CCS in sea which is also included in strategy III. A high and steady salmon price, as seen the last year, might justify these high investment costs.

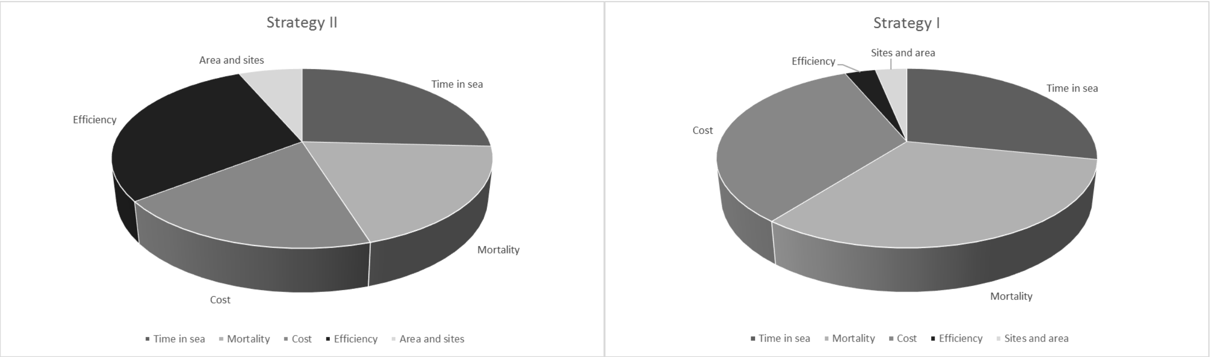
## 9.2 Criteria and results

The ROC and AHP analysis results in different recommended solutions. While the ROC method slightly favor strategy II, the AHP analysis favor strategy I with some margin. This can best be described by looking at the weight and ranking differences between the methods. In the ROC method the weight difference between criterion ranked as number two and three are significant, from 0.257 to 0.157. While in the AHP method these two criteria are weighted to be similar, 0.192. Table 9.1 displays the weight and level of importance of the criteria for ROC and AHP respectively, as well as the difference.

The ROC method favour strategy II while the AHP method favour strategy I. In figure 9.1 the two highest scoring strategies are compared. Due to the difference in the methods it is interesting to see how the different criteria affect the total score. Strategy II, in the ROC analysis, is made up evenly by every criteria, except the Sites and area-criterion. For strategy I, in the AHP analysis, there are three main contributors; Cost, Time in sea and Mortality. In theory the ROC method are known to get somewhat dispersed weights (F. H. Barron & Barrett, 1996), but in this case the AHP seems to make the two least important criteria almost eliminated to effect the analysis.

Table 9.1: Weight and importance of criteria in ROC and AHP respectively.

| **Criteria** | **ROC weight** | **AHP importance** | **Difference** |
|---|---:|---:|---:|
| Time in sea | 0.457 | 0.529 | 0.072 |
| Mortality | 0.257 | 0.192 | 0.065 |
| Cost | 0.157 | 0.192 | 0.035 |
| Efficiency | 0.090 | 0.058 | 0.032 |
| Area and sites | 0.040 | 0.030 | 0.010 |



(a) ROC recommended solution

(b) AHP recommended solution

Figure 9.1: Recommended strategy applying the two different methods; ROC and AHP. Strategy II and strategy I respectively, displaying the effect for each criteria. Small piece in the diagram indicates a low impact on the total score for the strategy.

Including other decision makers, like a fish farming company, representatives from law and regulations, fish farming operators or veterinarians could mean to add and adjust both criteria, alternatives and judgments. Selection of criteria is another aspect in the analysis that must be highlighted. The selected criteria are chosen due to their relationship to todays challenges and problems. Other aspects as increase production volume, number of handling, use of wellboats, number of delousing operations and amount of feed could have been other criteria to evaluate strategies upon. Recommended solutions only take into account the actual criteria applied, so changing or increasing criteria could potentially mean changing the final results considerably. This limits the value of the results gained in the analysis.

## 9.3 Assumptions

Assumptions related to the criteria selected are important, due to simplification and restriction of the study. Especially the assumption related to allowed density is affecting the analysis significantly. The amount of production units needed if the 200 000 limit is valid for systems like Neptun would be huge. If Neptun is compared to other systems, like Preline which was presented in chapter 3, the density assumption seems even more relevant. Due to the great difference in volume between Neptun and the other presented systems, the number of units required to produce postsmolt up to one kilogram would be enormous. Assuming that it would be realistic to produce all smolt in Norway up to one kilogram in S-CCS floating in sea, may also seem controversial. This is done to have some actual data to review these systems up against.

Success in research and pilot testing are not equal to success in commercial scale production. It is important to emphasize that full scale testing is extremely relevant to achieve success in a commercial scale production. Pilot testing and research are often conducted with specifications slightly different from what will be the fact in production. For instance density, fish size, volume, water velocity, water source, hydraulic retention time and feed management. Production environment is affected by this and the results for a given range of these parameters might not be directly scalable to commercial production ranges.

Strategies proposed by the author are based on previous proposals by industry and researchers, as well as discussion with industry actors. Rearing postsmolt up to one kilogram in closed and semi-closed systems in sea and on land has been a clear vision for some time. Due to the increased weight of dead-fish and rapid increase in production cost it could be of interest to use these systems in other parts of the production cycle. For simplicity the strategies presented are applying S-CCS for the last stage of the production cycle. It could and should also be investigated if it is other size ranges where these systems could be put into use. Seasonal variation in the environment for each region, like water quality, problems with sealice and diseases, and algae bloom could be decisive for when Atlantic salmon should be produced in S-CCS.

## 9.4 Atlantic salmon production

Variation in production of Atlantic salmon along the Norwegian coast is important to keep in mind. Some sites and areas are more suitable for production and some sites struggle and are far from optimal. This makes it difficult to suggest a strategy that would be suitable for all the production along the coast. The sites that rarely struggle with sealice, diseases and maintains a low mortality rate would probably not benefit by systems proposed in this study. On the other hand, sites struggling could benefit from some of these suggestions. It is more realistic that the industry will develop all or some of these systems in parallel and apply them to sites to utilize their advantages. Companies having the opportunity to expand an existing landbased smolt facility would probably take this advantage and produce bigger smolt by expanding rather than focusing on S-CCS floating in sea. There are many considerations to be taken. Regional differences, focus and strategies of companies and existing strengths are some of them.

Development of other strategies, as exposed aquaculture, could also affect the production strategies. Exposed aquaculture could increase production volume, but might be dependant of more robust fish or larger smolt. This can lead to a development that exploits the different qualities of the different production systems and by that optimizing the production in total.

If semi-closed containment systems floating in sea are to be reliable and productive they must be able to operate with a low risk of getting diseases into the rearing environment. Success of production in S-CCS are highly dependant on effective water treatment solutions and technology. Arguments for producing in S-CCS are dependant on proving that the production method is better compared to todays production. Better means to eliminate todays challenges and improve production on criteria like efficiency, mortality and increase in volume. Water treatment is highly relevant to achieve this, and are in this study assumed to be solved.

It is not only investment cost that must be considered when evaluating the new production strategies. Operational cost should also be included. In this study the production cost are not included in the analysis, but mentioned as a argument for developing new production systems. Salmon price is just as important as the costs as it might determine and defend the higher investment and production cost. It is simplified in this study.

## 9.5 Comments of the study

This study are a limited to the proposed criteria and strategies. Results from the analysis can not be seen as optimal solution in any way, but more as en example of how new production strategies can be evaluated. When more results and knowledge are acquired, the criteria can be quantified in more depth building a better model and basis for evaluation.

## Chapter 10

# Conclusion

In the near future postsmolt production up to a weight of one kilogram seems likely to be conducted in S-CCS floating in sea. Parallel to this is the development in landbased postsmolt production aspiring. So far there are no documentation indicating that production of fish close to market size will be produced in S-CCS in near future.

Strategy I proposed in this study seems most likely to be realistic and feasible. It will not be the only choice for further development related to postsmolt production as landbased postsmolt production is evolving. The method used to evaluate the alternatives in this study can be used as aid for decision makers to quantify their preferences and possibilities in strategy related issues.

Before production in S-CCS will be commercially available the knowledge gap must be narrowed and documentation related to production must be acquired. Sufficient and reliable water treatment must be in place, water exchange and fish densities must be set in order to implement the systems into todays production regime.

Applying S-CCS for postsmolt production up to a weight of one kilogram is a realistic and clear vision in the future of Atlantic salmon production in Norway. Based on the success of this development, it might be incentives to expand the production to include fish close to market size or even for the whole life cycle.

Changes in production cost, due to reduced challenges like sealice and diseases, combined with declining price of Atlantic salmon can be seen as external factors that may influence or even stagnate the development of closed and semi-closed production systems. Another important factor regarding this is the development of the traditional open net pen system. There are still opportunities for improvement of this production method.

## 10.1 Thesis claims

Before answering the claims stated in the problem description it is important to emphasize that there are a lot of unknowns related to answering these questions and there are simplifications and assumptions involved in the judgments in this study.

**1.** Introducing S-CCS to Atlantic salmon farming can increase production volume and increase efficiency of sea sites.

- Yes, if the results from research regarding mortality and reduced number of operations are scalable to commercial production, the reduction in loss will be gained production volume. Combined with this will the reduced time exposed in sea reduce the number of operations related to handling of the fish, resulting in less starvation time of fish during production. These two potential benefits can increase production volume slightly.

- Efficiency of sea sites can potentially increase. Restocking sea sites with bigger fish will result in a more efficient production, as the site will produce closer to maximum allowed biomass earlier in production stage. Sites will also be restocked quicker because of the reduced time exposed in sea. There might be problems related to law and regulations concerning this topic.

**2.** S-CCS can reduce the amplitude in the cyclic production of salmon and keep a more stable production near maximum allowed biomass.

- Yes and no. As mentioned above, producing closer to maximum allowed biomass can somewhat reduce the fluctuations in production, but production of Atlantic salmon will still be a cyclic process changing throughout the year as the biomass grows.

**3.** S-CCS will reduce exposure in open sea and handling of fish required, resulting in a higher degree of fish welfare and health.

- Yes, S-CCS can reduce the time exposed in sea significantly. It is not possible to say that the fish welfare and health will be improved by introducing the S-CCS in commercial scale production yet. The potential for control indicates that fish welfare and health can be improved.

# Chapter 11

# Further work

This study can be seen as a introduction to how semi-closed containment systems can be implemented in the production regime, but there are many aspects not taken into account in this thesis. There are many opportunities for a lot of further work to be done within this area. Using it as a basis for understanding what S-CCS are and seeing it in connection with todays production regime are probably the most reasonable.

Building a mathematical model to simulate production in S-CCS will be of interest. It will be important to include essential parameters related to water quality as well as growth. If the model of production in S-CCS is linked to an model of open net pen production it can highlight the utilization of both the S-CCS and the sea site production. Making an integrated mathematical model of this can be of interest for the industry to identify the logistical challenges and opportunities.

Design of a S-CCS production unit can be a challenging task to embark on. Especially if water treatment technologies and waste systems must be implemented in the design. This makes the systems more complex and the need to design reliable and functional production units will be crucial. Focus on the process and structural design will be of interest.

Another interesting task can be to define other strategies regarding Atlantic salmon, like investigating if there are incentives for producing in S-CCS at specific periods during a year rather than for specific weight ranges. This task may have a more biological approach.

Comparing postsmolt production up to a weight of one kilogram in S-CCS and landbased units can definitely be interesting. Economically, biological, environmental and technological approaches could be interesting.

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# Appendix A

# ROC

ROC weights

| **Criteria** | **Ranking** | **Weight** |
|---|---|---|
| Time in sea | 1 | 0,457 |
| Mortality | 2 | 0,257 |
| Cost | 3 | 0,157 |
| Efficiency | 4 | 0,090 |
| Area and sites | 5 | 0,040 |
| Total | | 1,000 |

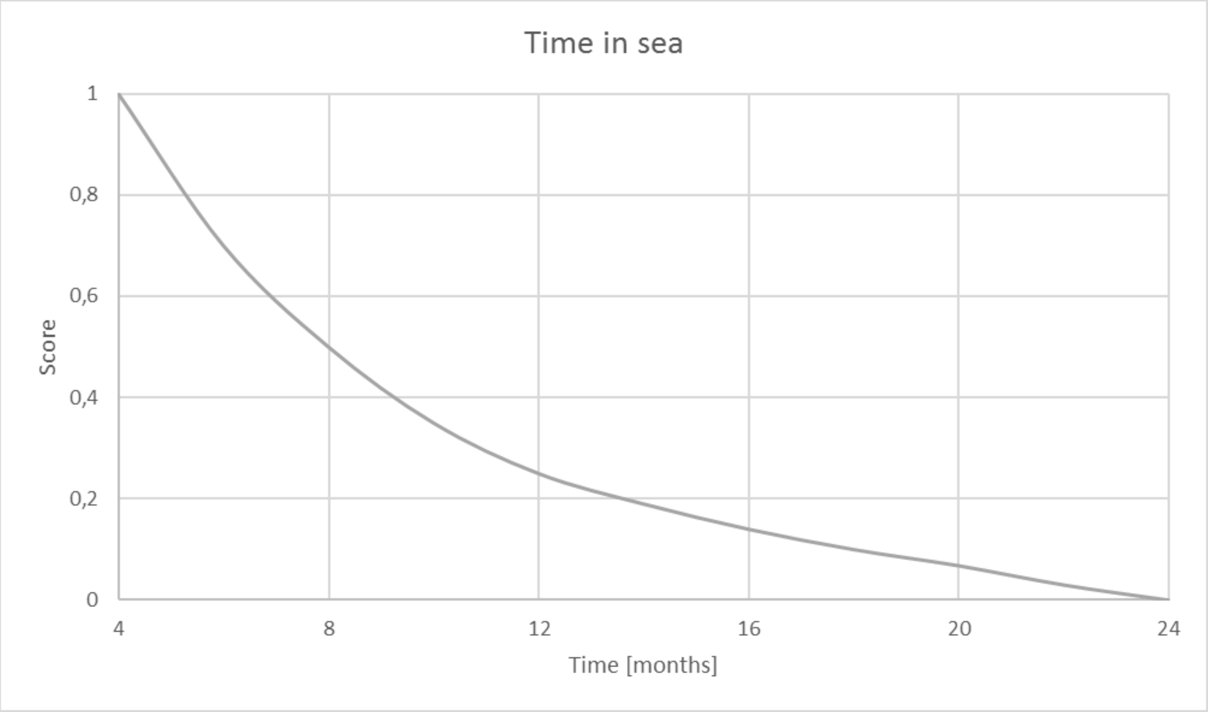
ROC score table

| | **I** | **II** | **III** |
|---|---|---|---|
| Time in sea | 0,7 | 0,8 | 0,8 |
| Mortality | 0,6 | 0,6 | 0,8 |
| Cost | 1,0 | 0,6 | 0,1 |
| Efficiency | 0,6 | 0,9 | 0,9 |
| Sites and area | 0,4 | 0,2 | 0,2 |

ROC results

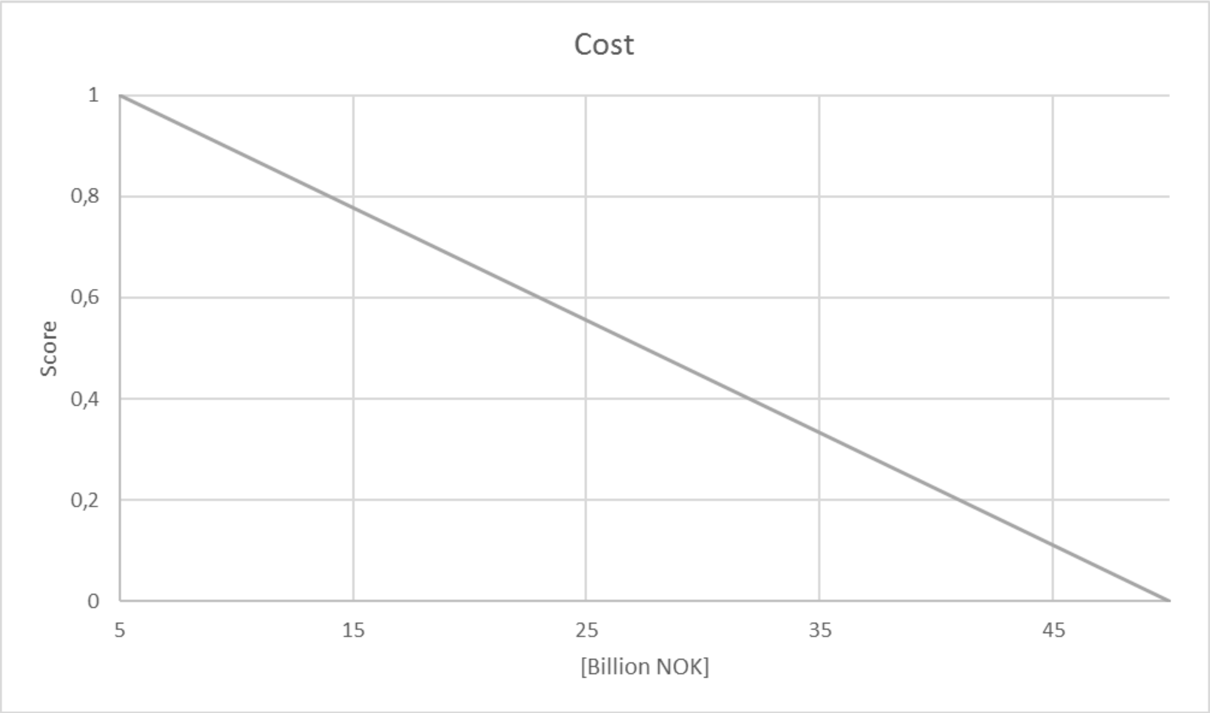
| **Criteria** | **Ranking** | **Weight** | **I** | **II** | **III** |
|---|---|---|---|---|---|
| Time in sea | 1 | 0,457 | 0,700 | 0,800 | 0,800 |
| Mortality | 2 | 0,257 | 0,600 | 0,600 | 0,800 |
| Cost | 3 | 0,157 | 1,000 | 0,600 | 0,100 |
| Efficiency | 4 | 0,090 | 0,600 | 0,900 | 0,900 |
| Area and sites | 5 | 0,040 | 0,400 | 0,200 | 0,200 |
| Total | | 1,000 | 0,700 | 0,702 | 0,675 |

## Value functions

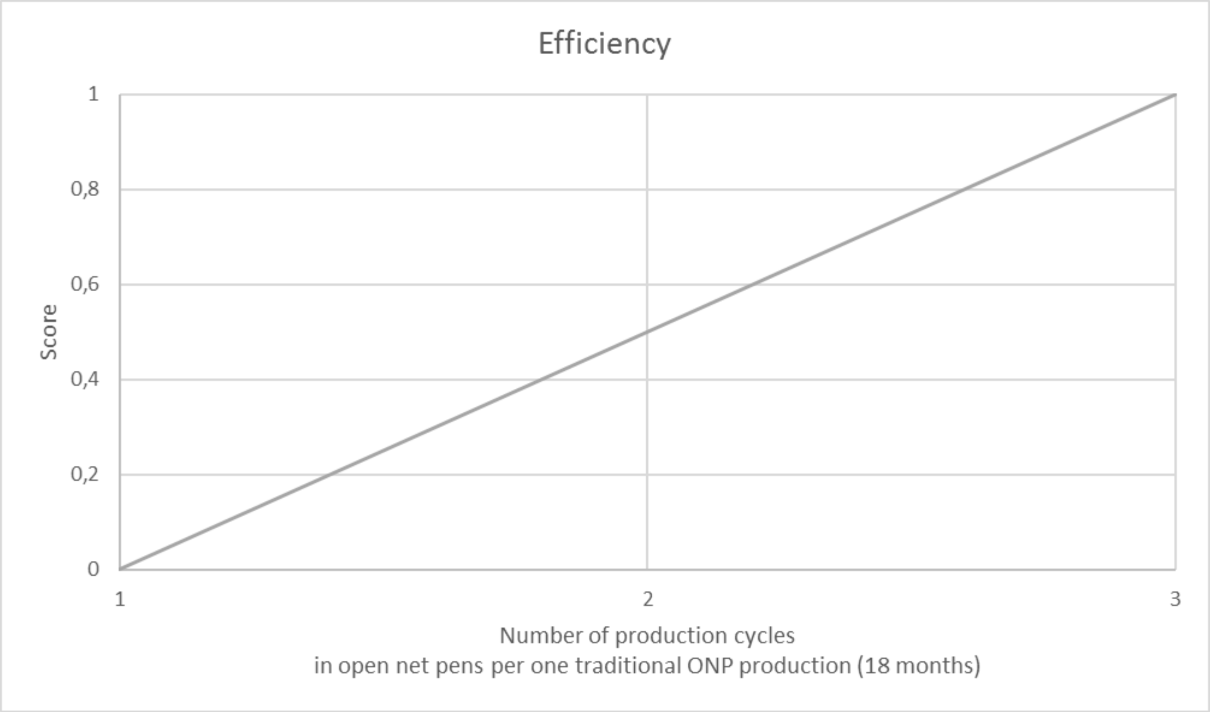


Time in sea

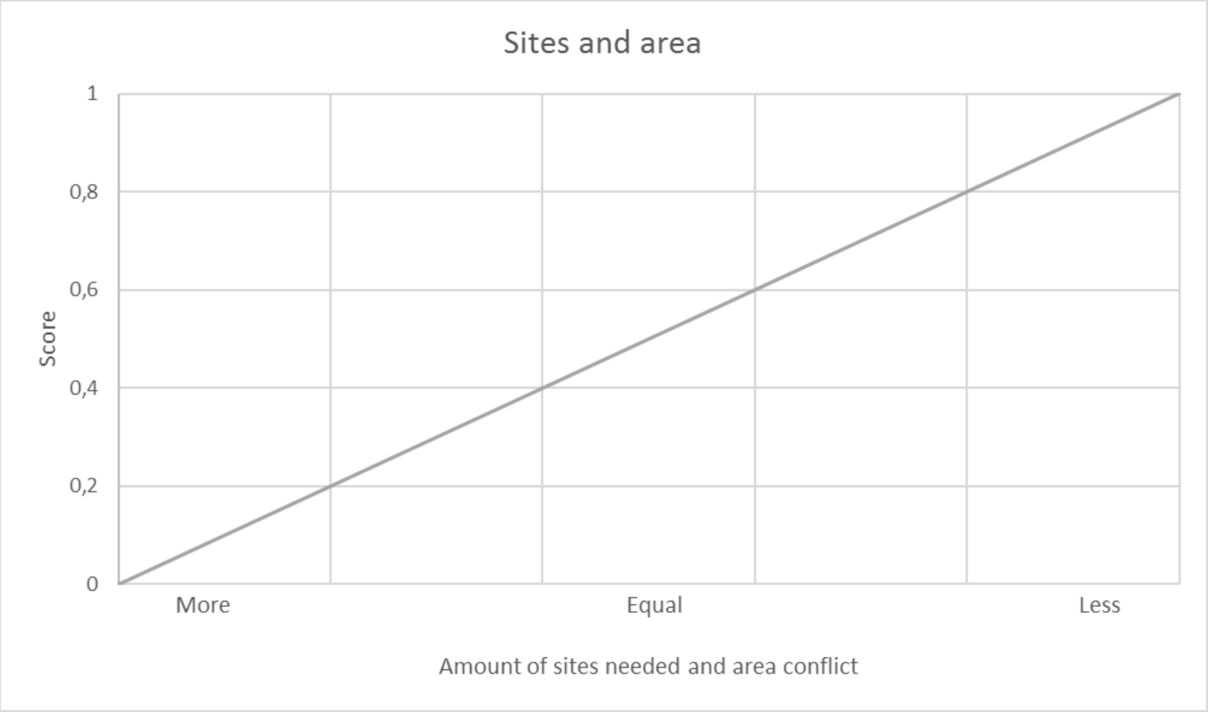
Mortality



Cost



Efficiency



Sites and area

# Appendix B

# AHP

Criteria comparison matrix

| | **Time in sea** | **Mortality** | **Cost** | **Efficiency** | **Sites and area** |
|---|---|---|---|---|---|
| Time in sea | 1 | 5 | 5 | 7 | 9 |
| Mortality | 1/5 | 1 | 1 | 5 | 9 |
| Cost | 1/5 | 1 | 1 | 5 | 9 |
| Efficiency | 1/7 | 1/5 | 1/5 | 1 | 3 |
| Sites and area | 1/9 | 1/9 | 1/9 | 1/3 | 1 |

Normalized criteria comparison matrix

| | **Time in sea** | **Mortality** | **Cost** | **Efficiency** | **Sites and area** |
|---|---|---|---|---|---|
| Time in sea | 0,60 | 0,68 | 0,68 | 0,38 | 0,29 |
| Mortality | 0,12 | 0,14 | 0,14 | 0,27 | 0,29 |
| Cost | 0,12 | 0,14 | 0,14 | 0,27 | 0,29 |
| Efficiency | 0,09 | 0,03 | 0,03 | 0,05 | 0,10 |
| Sites and area | 0,07 | 0,02 | 0,02 | 0,02 | 0,03 |

Level of importance for criteria

| **Criteria** | **Level of importance** |
|---|---|
| Time in sea | 0,53 |
| Mortality | 0,19 |
| Cost | 0,19 |
| Efficiency | 0,06 |
| Sites and area | 0,03 |

Consistency check for criteria comparison matrix

| | **Average** | **Consistency Measure** |
|---|---|---|
| Time in sea | 0,53 | 5,90 |
| Mortality | 0,19 | 5,47 |
| Cost | 0,19 | 5,47 |
| Efficiency | 0,06 | 5,12 |
| Sites and area | 0,03 | 5,08 |
| | | |
| Average consistency | 5,41 | |
| CI | 0,10 | |
| RI | 1,12 | |
| Consistency ratio | 0,09 | |
| Consistent? | Yes | |

Comparison matrix for the criterion *Time in sea.*

| **Time in sea** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 1,0 | 1/2 | 1/2 |
| Strategy II | 2,0 | 1,0 | 1,0 |
| Strategy III | 2,0 | 1,0 | 1,0 |

Normalized comparison matrix for the criterion *Time in sea.*

| **Time in sea** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 0,20 | 0,20 | 0,20 |
| Strategy II | 0,40 | 0,40 | 0,40 |
| Strategy III | 0,40 | 0,40 | 0,40 |

Consistency check for the criterion *Time in sea.*

| **Time in sea** | Row average | Consistency Measure |
|---|---|---|
| Strategy I | 0,20 | 3,00 |
| Strategy II | 0,40 | 3,00 |
| Strategy III | 0,40 | 3,00 |
| | | |
| Average consistency | 3 | |
| CI | 0 | |
| RI | 0,58 | |
| Consistency | 0 | |
| Consistent? | Yes | |

Comparison matrix for the criterion *Mortality*.

| **Mortality** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 1 | 5 | 3 |
| Strategy II | 1/5 | 1 | 1/3 |
| Strategy III | 1/3 | 3 | 1 |

Normalized comparison matrix for the criterion *Mortality*.

| **Mortality** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 0,65 | 0,56 | 0,69 |
| Strategy II | 0,13 | 0,11 | 0,08 |
| Strategy III | 0,22 | 0,33 | 0,23 |

Consistency check for the criterion *Mortality*.

| **Mortality** | Row average | Consistency Measure |
|---|---|---|
| Strategy I | 0,63 | 3,07 |
| Strategy II | 0,11 | 3,01 |
| Strategy III | 0,26 | 3,03 |
| Average consistency | 3,04 | |
| CI | 0,02 | |
| RI | 0,58 | |
| Consistency | 0,03 | |
| Consistent? | Yes | |

Comparison matrix for the criterion *Cost*.

| **Cost** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 1 | 3 | 9 |
| Strategy II | 1/3 | 1 | 7 |
| Strategy III | 1/9 | 1/7 | 1 |

Normalized comparison matrix for the criterion *Cost*.

| **Cost** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 0,69 | 0,72 | 0,53 |
| Strategy II | 0,23 | 0,24 | 0,41 |
| Strategy III | 0,08 | 0,03 | 0,06 |

Consistency check for the criterion *Cost*.

| **Cost** | Row average | Consistency Measure |
|---|---|---|
| Strategy I | 0,65 | 3,15 |
| Strategy II | 0,29 | 3,08 |
| Strategy III | 0,06 | 3,01 |
| | | |
| Average consistency | 3,08 | |
| CI | 0,04 | |
| RI | 0,58 | |
| Consistency | 0,07 | |
| Consistent? | Yes | |

Comparison matrix for the criterion *Efficiency*.

| **Efficiency** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 1 | 1/2 | 1/2 |
| Strategy II | 2 | 1 | 1 |
| Strategy III | 2 | 1 | 1 |

Normalized comparison matrix for the criterion *Efficiency*.

| **Efficiency** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 0,20 | 0,20 | 0,20 |
| Strategy II | 0,40 | 0,40 | 0,40 |
| Strategy III | 0,40 | 0,40 | 0,40 |

Consistency check for the criterion *Efficiency*.

| **Efficiency** | Row average | Consistency Measure |
|---|---|---|
| Strategy I | 0,20 | 3,00 |
| Strategy II | 0,40 | 3,00 |
| Strategy III | 0,40 | 3,00 |
| | | |
| Average consistency | 3,0 | |
| CI | 0,0 | |
| RI | 0,58 | |
| Consistency | 0,0 | |
| Consistent? | Yes | |

Comparison matrix for the criterion *Sites and area.*

| **Sites and area** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 1 | 3 | 1 |
| Strategy II | 1/3 | 1 | 1/5 |
| Strategy III | 1 | 5 | 1 |

Normalized comparison matrix for the criterion *Sites and area.*

| **Sites and area** | Strategy I | Strategy II | Strategy III |
|---|---|---|---|
| Strategy I | 0,43 | 0,33 | 0,45 |
| Strategy II | 0,14 | 0,11 | 0,09 |
| Strategy III | 0,43 | 0,56 | 0,45 |

Consistency check for the criterion *Sites and area.*

| **Sites and area** | Row average | Consistency Measure |
|---|---|---|
| Strategy I | 0,41 | 3,03 |
| Strategy II | 0,11 | 3,01 |
| Strategy III | 0,48 | 3,04 |
| | | |
| Average consistency | 3,03 | |
| CI | 0,01 | |
| RI | 0,58 | |
| Consistency | 0,03 | |
| Consistent? | Yes | |

Criteria preference matrix

| **Criteria Preference Matrix** | | | | | |
|---|---|---|---|---|---|
| **Alternative** | Time in sea | Mortality | Cost | Efficiency | Sites and area |
| Strategy I | 0,20 | 0,63 | 0,65 | 0,20 | 0,41 |
| Strategy II | 0,40 | 0,11 | 0,29 | 0,40 | 0,11 |
| Strategy III | 0,40 | 0,26 | 0,06 | 0,40 | 0,48 |

Level of importance for criteria

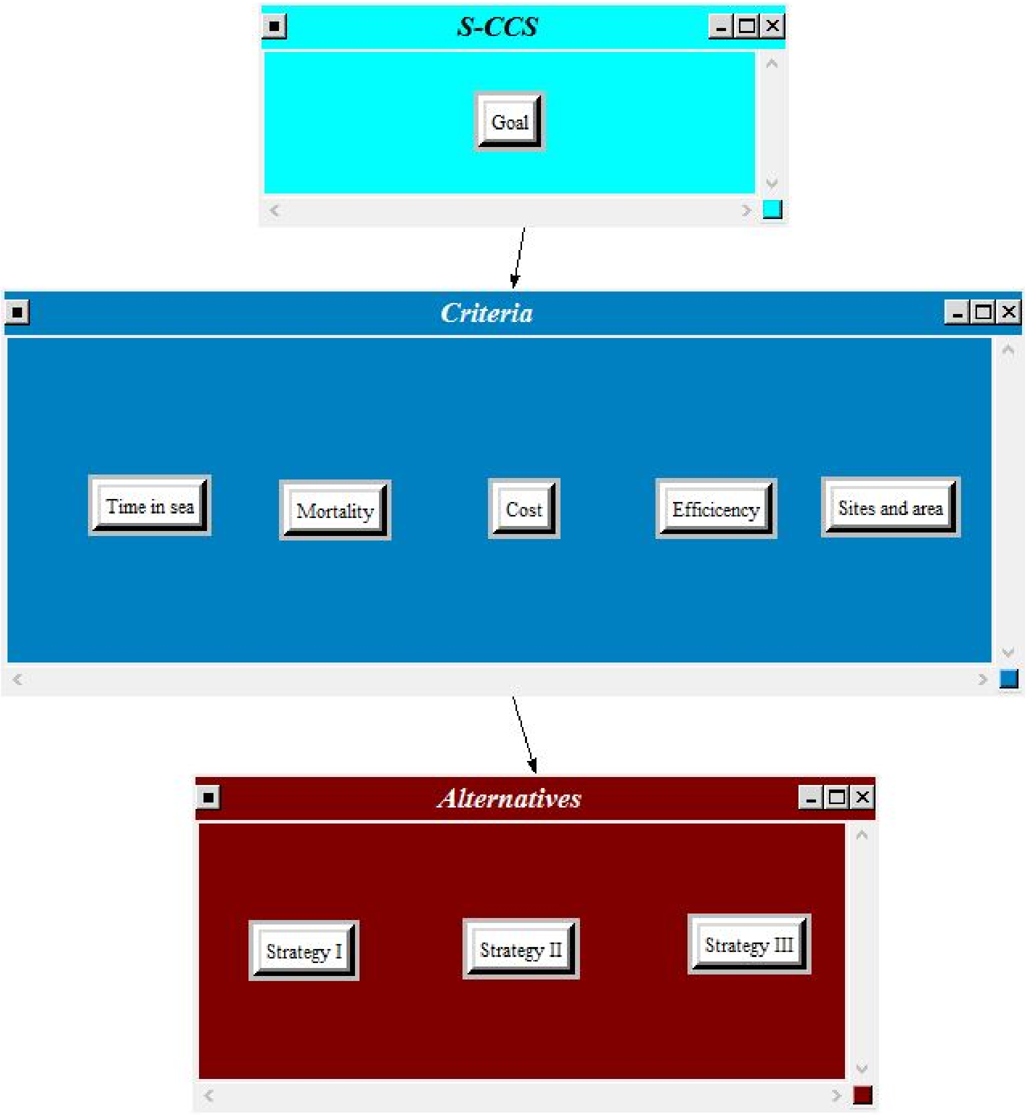
| **Criteria** | **Level of importance** |
|---|---|
| Time in sea | 0,53 |
| Mortality | 0,19 |
| Cost | 0,19 |
| Efficiency | 0,06 |
| Sites and area | 0,03 |

Calculated strategy-score for each criterion.

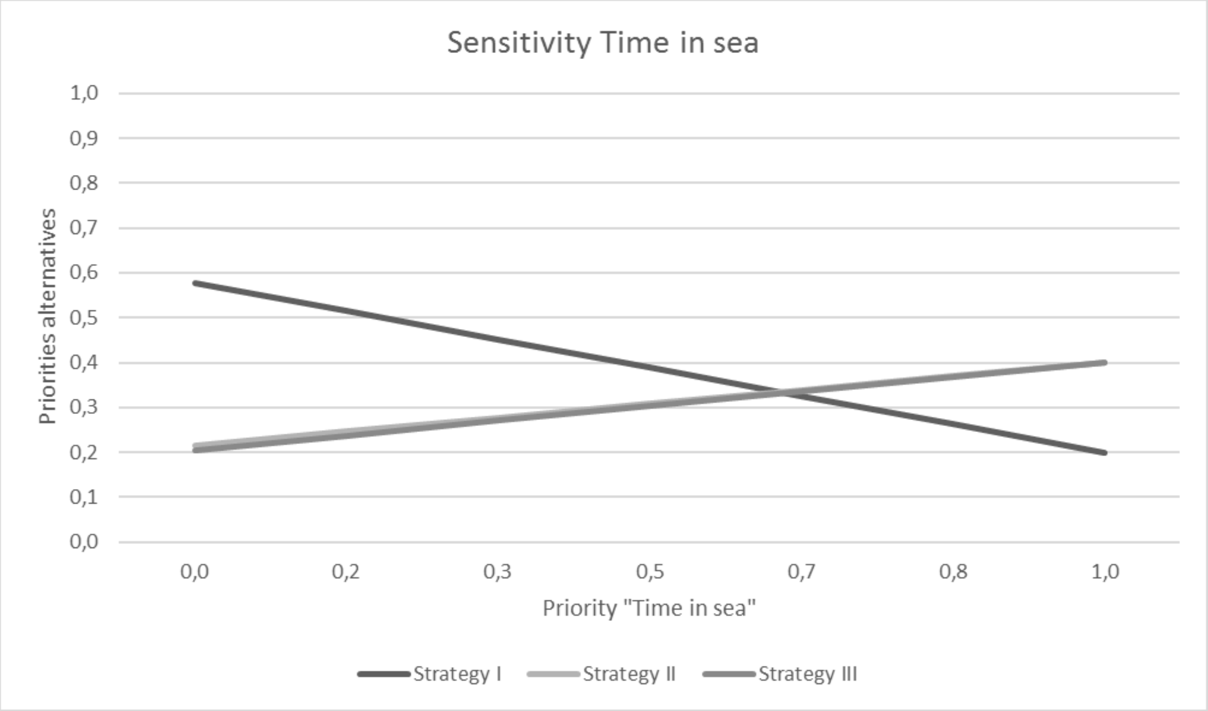
| | **Time in sea** | **Mortality** | **Cost** | **Efficiency** | **Sites and area** | **Score** |
|---|---|---|---|---|---|---|
| Strategy I | 0,106 | 0,121 | 0,124 | 0,012 | 0,012 | 0,375 |
| Strategy II | 0,212 | 0,020 | 0,056 | 0,023 | 0,003 | 0,315 |
| Strategy III | 0,212 | 0,050 | 0,011 | 0,023 | 0,014 | 0,310 |

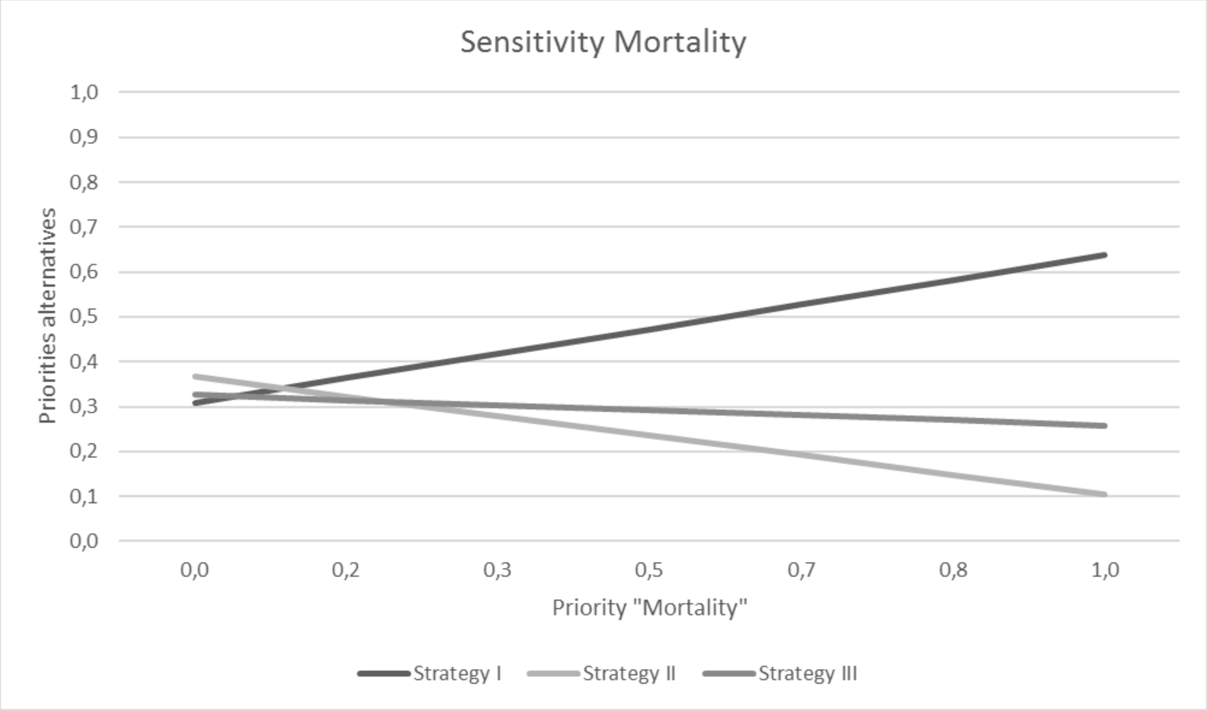
# Appendix C

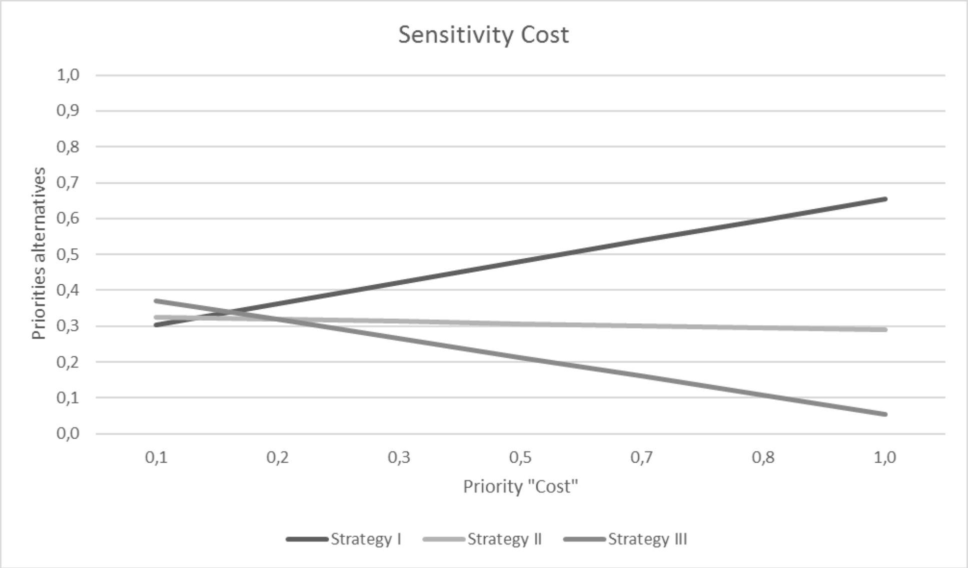
# Sensitivity analysis

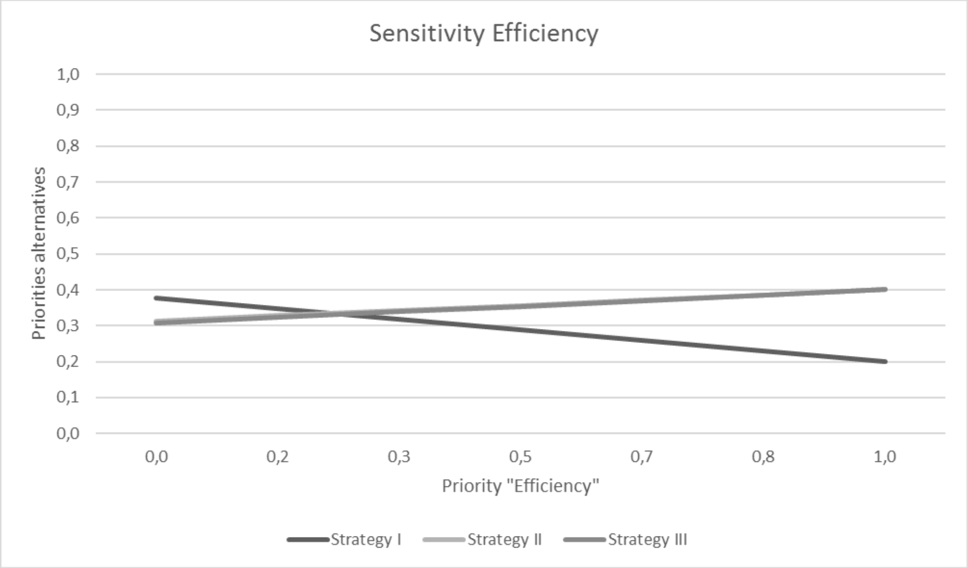


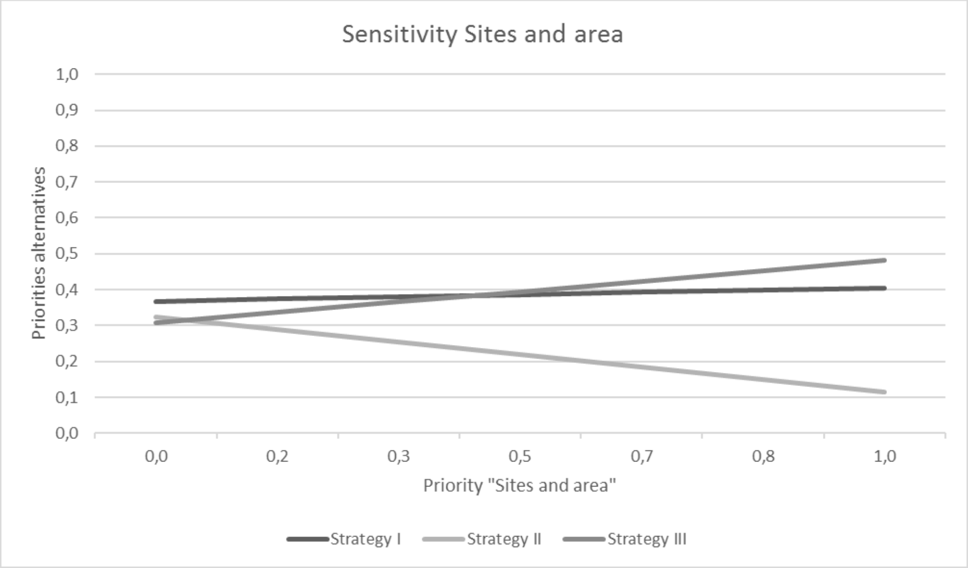
Selection of the model in SuperDecisions free software, used to compute sensitivity analysis.


Sensitivity Time in sea
Priorities alternatives
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
0,0
0,2
0,3
0,5
0,7
0,8
1,0
Priority "Time in sea"
Strategy I
Strategy II
Strategy III


Sensitivity Mortality
Priorities alternatives
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
0,0
0,2
0,3
0,5
0,7
0,8
1,0
Priority "Mortality"
Strategy I
Strategy II
Strategy III


Sensitivity Cost
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
Priorities alternatives
0,1
0,2
0,3
0,5
0,7
0,8
1,0
Priority "Cost"
Strategy I
Strategy II
Strategy III


Sensitivity Efficiency
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
Priorities alternatives
0,0
0,2
0,3
0,5
0,7
0,8
1,0
Priority "Efficiency"
Strategy I
Strategy II
Strategy III


Sensitivity Sites and area
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
Priorities alternatives
0,0
0,2
0,3
0,5
0,7
0,8
1,0
Priority "Sites and area"
Strategy I
Strategy II
Strategy III